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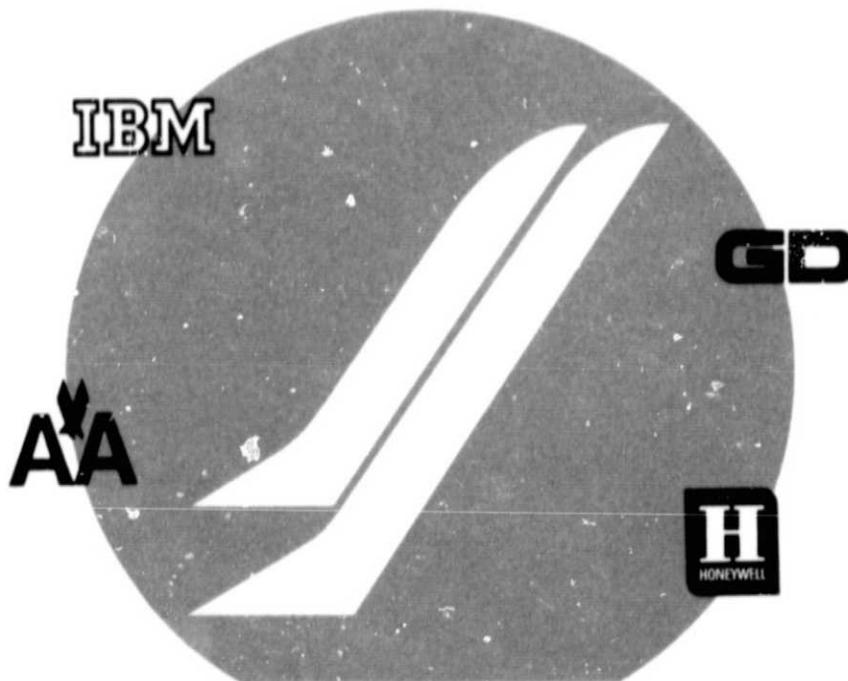
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Space Shuttle Program

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FINAL SUBMITTAL



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REUSABLE SPACE SHUTTLE BOOSTER. VOLUME
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Phase B Final Report Expendable Second Stage Reusable Space Shuttle Booster Volume III. Wind Tunnel Test Data

Contract NAS9-10960, Exhibit B
DRL MSFC-DRL-221, DRL Line Item 6
DRD MA-078-U2
SD 71-140-3
25 June 1971



SD 71-140-3
(MSC-03321)

25 June 1971

PHASE B FINAL REPORT
EXPENDABLE SECOND STAGE
REUSABLE SPACE SHUTTLE BOOSTER

Volume III
Wind Tunnel Test Data

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Approved by

B. Hello
Vice President and General Manager
Space Shuttle Program



FOREWORD

The Space Shuttle Phase B studies are directed toward the definition of an economical space transportation system. In addition to the missions which can be satisfied with the shuttle payload capability, the National Aeronautics and Space Administration has missions planned that require space vehicles to place payloads in excess of 100,000 pounds in earth orbit. To satisfy this requirement, a cost-effective multimission space shuttle system with large lift capability is needed. Such a system would utilize a reusable shuttle booster and an expendable second stage. The expendable second stage would be complementary to the space shuttle system and impose minimum impact on the reusable booster.

To assist the expendable second stage concept, a two-phase study was authorized by NASA. Phase A efforts, which ended in December 1970, concentrated on performance, configuration, and basic aerodynamic considerations. Basic trade studies were carried out on a relatively large number of configurations. At the conclusion of Phase A, the contractor proposed a single configuration. Phase B commenced on February 1, 1971 (per Technical Directive Number 503) based on the recommended system. Whereas a large number of payload configurations were considered in the initial phase, Phase B was begun with specific emphasis placed on three representative payload configurations. The entire Phase B activity has been directed toward handling the three representative payload configurations in the most acceptable manner. Results of this activity are reported in this 12-volume Phase B final report.

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Volume II	Technical Summary	SD 71-140-2
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Volume VII	Preliminary Design Drawings	SD 71-140-7
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Volume IX	Preliminary System Specification	SD 71-140-9
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Volume XI	Cost and Schedule Estimates	SD 71-140-11
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This is Volume III, Wind Tunnel Test Data, SD 71-140-3.

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1.0 INTRODUCTION

The prime objectives of the Expendable Second Stage (ESS) Study are to (1) determine the feasibility and cost effectiveness and (2) provide a preliminary design of a system which will be suitable for a wide variety of advanced space missions beginning in the last half of calendar year 1979. The overall system is intended to meet evolving NASA/DOD system requirements with the most economical usage of shuttle/ESS system elements.

The space shuttle orbiter vehicle has a cargo bay which is 15 feet in diameter by 60 feet in length. Hence, payloads for the orbiter must fit into the established cargo bay. Payloads larger than the cargo bay can be considered under the concept by which the ESS would be mounted on the reusable booster. The three NASA-specified payload configurations cover the spectrum of anticipated payloads. The payload variables include weight, size, and shape.

To evaluate the flight characteristics of the several ESS/payload configurations on the reusable booster, NASA/MSFC provided for and supported a wind tunnel program to include the appropriate speed, angle of attack, and Reynolds number ranges to evaluate the aerodynamic characteristics. Scale models of the selected ESS, with three payload forebody shapes, were constructed. The available space shuttle booster model was the GDC configuration B-15B-1 booster. This model is nominally 0.0035 scale. However, the GDC B-9U booster configuration has been selected for the shuttle baseline. The available model body length is representative of the GDC B-9U booster to 0.0031 scale. Because the ESS is baselined with the B-9U booster, the ESS/payload configurations were built to 0.0031 scale. The three specified payload shapes were as follows: (1) space station (MDAC), single-launch configuration; (2) nuclear stage without engine (reusable nuclear stage, RNS); and (3) space tug, geosynchronous mission. Data obtained for each of these configurations required appropriate correction to permit comparison with estimated data (as given in Volume 2, Technical Summary, SD 71-140-2). The tests were conducted in the MSFC 14-inch-by-14-inch trisonic wind tunnel from April 22 to April 24, 1971. Overall test objectives were as follows:

1. Establish launch vehicle aerodynamic performance characteristics.
2. Determine launch vehicle stability characteristics.
3. Determine booster roll control effectiveness.



Data for the booster/ESS/MDAC configuration were obtained in test section Mach numbers of 0.6, 0.9, 1.0, 1.2, 2.0, 3.0, 5.0. The booster/ESS/RNS and booster/ESS/space tug configurations were evaluated at test section Mach numbers of 1.2 and 3.0.

This volume includes the nomenclature associated with the test, a description of the models, and a brief discussion of the aerodynamic characteristics derived from the tests.



2.0 NOMENCLATURE

The nomenclature used in presenting the results of the analysis is given in this section. Lateral-directional characteristics (C_Y , C_L , C_N) are in the body axes system. Dimensions shown are to model scale.

2.1 GENERAL

A	Axial force, pounds
b_{ref}	Booster reference wing span, 6.099 inches
\bar{c}	Booster wing mean aerodynamic chord, 3.095 inches
L_B	Booster body length, 9.734 inches
M	Mach number
PITCH ac	Aerodynamic center in pitch, percent booster length
q	Dynamic pressure, pounds per square foot
S_{ref}	Booster reference wing area, 15.656 square inches
YAW ac	Aerodynamic center in yaw, percent booster length
α	Angle of attack, degrees
$(\alpha = 0)$	Parameter evaluated at zero angle-of-attack
β	Angle of sideslip, degrees
δ	Control surface deflection, δ_R rudder, δ_E elevon
λ	Taper ratio
Γ	Dihedral angle, degrees
Λ	Sweep angle, degrees
Δ	Increment



2.2 AERODYNAMIC COEFFICIENTS

C_{A_F}	Forebody axial force coefficient, $\frac{\text{forebody axial force}}{q S_{\text{ref}}}$
C_l	Rolling moment coefficient, $\frac{\text{rolling moment}}{q S_{\text{ref}} b_{\text{ref}}}$
$C_{l\beta}$	Lateral stability, $\frac{dC_l}{d\beta}$, per degree
$C_{l\delta_E}$	Rolling moment coefficient due to elevon deflection, $\frac{dC_l}{d\delta_E}$, per degree differential
$C_{l\delta_R}$	Rolling moment coefficient due to rudder deflection, $\frac{dC_l}{d\delta_R}$
C_m	Pitching moment coefficient, $\frac{\text{pitching moment}}{q S_{\text{ref}} \bar{c}}$
$\frac{dC_m}{dC_N}$	Pitch stability
C_N	Normal force coefficient, $\frac{\text{normal force}}{q S_{\text{ref}}}$
C_n	Yawing moment coefficient, $\frac{\text{yawing moment}}{q S_{\text{ref}} b_{\text{ref}}}$
$C_{n\beta}$	Directional stability, $\frac{dC_n}{d\beta}$, per degree
$C_{n\delta_R}$	Yawing moment coefficient due to rudder deflection, per degree
C_Y	Side force coefficient, $\frac{\text{side force}}{q S_{\text{ref}}}$
$C_{Y\beta}$	Side force curve slope, per degree
$\frac{dC_n}{dC_Y}$	Yaw stability



3.0 MODEL DESCRIPTION

Three 0.0031 scale models of an S-II booster with three different fore-body shapes were constructed to represent respectively the ESS/RNS, ESS/MDAC, and ESS/space tug configurations. Dimensional data are presented for these configurations in Table 3-1 and dimensioned sketches are presented in Figure 3-1.

Table 3-1. ESS Stages Model Geometry

Dimensions (model scale)	ESS	MDAC	RNS	ST
Length, inches	2.945	4.247	6.510	3.875
Diameter, inches	1.228	1.228	1.228	0.558
Area (X-sec), square inches	1.184	1.184	1.184	0.2445
Cone semi-apex angle, degrees	25.0	25.0	25.0	25.0
Frustum semi-apex angle, degrees	-	-	12.5	16.6
Hemispherical nose radius, inches	-	0.103	0.074	0.049
<p>Notes:</p> <ol style="list-style-type: none">1. Models are 0.0031 scale.2. Ependable second stage configurations are: $U = \text{ESS} + \text{MDAC (space station)}$ $U_2 = \text{ESS} + \text{RNS (reusable nuclear shuttle)}$ $U_3 = \text{ESS} + \text{ST (space tug)}$				

The booster is a 0.0035 scale model of the GDC (B-15B-1) booster configuration. The model has a wing area of 15.656 square inches, a mean aerodynamic chord of 3.095 inches, and an actual wing span of 6.099 inches. The body length is 9.734 inches with canards of symmetrical section mounted at zero incidence and dihedral angles. The canards have zero twist with



57.7 degrees leading edge sweep and an exposed taper ratio of 0.1058 . The wing has a 0.1061 taper ratio and 53 degrees of leading edge sweep. It is symmetrical in section and mounted at +2.0 degrees incidence at the root section, washing out to -2.0 degrees at the tip. Dihedral angle is +3.0 at the wing trailing edge. The top center aft fuselage mounted vertical has an exposed area of 2.247 square inches with 35 degrees leading edge sweep and 0.5 taper ratio. Table 3-2 presents dimensions of the booster and Figure 3-2 presents dimensioned drawings of the various booster components.

Figure 3-3 presents a drawing of the ESS launch configurations and Figure 3-4 is a dimensioned model drawing of the ESS launch configurations.

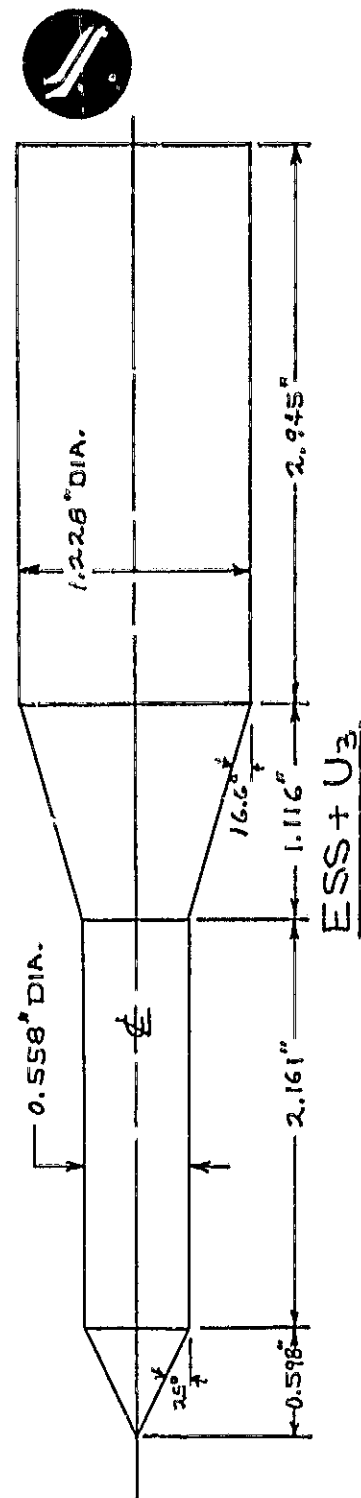
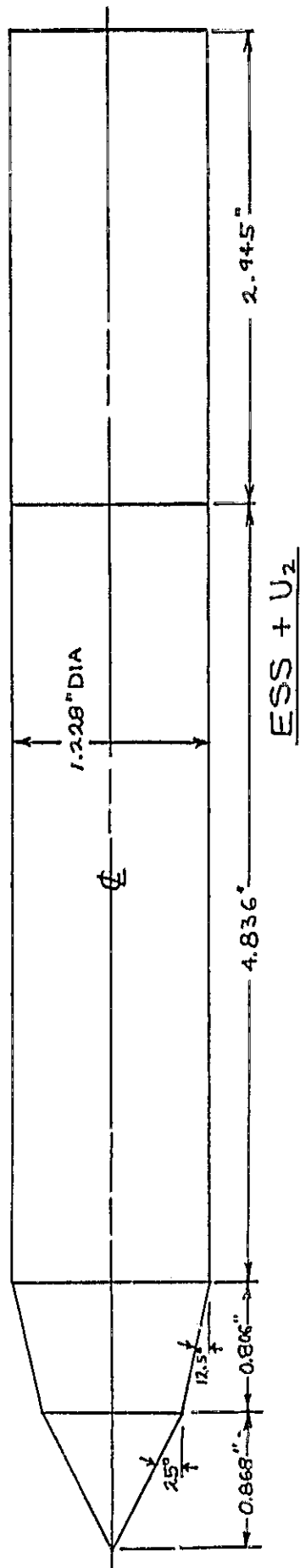


Figure 3-1. ESS Stages Model Geometry



Table 3-2. Booster Model Geometry

DELTA WING BOOSTER CONFIGURATION (B19C4W14V7): B19 Body (Basic body for B-15B-1 Booster including eight peripheral rocket engines and fairings)	
Dimensions	Model Scale
Length	9.734 inch
Max width	1.354 inch
Max depth	1.587 inch
Fineness ratio	6.08 inch
Area	
Max cross-sectional	2.252 inch ²
Planform	12.381 inch ²
Base (total)	1.837 inch ²
BALANCE CHAMBER	0.785 inch ²
Geometric balance center	
Dist aft of booster nose	6.380 inch
W. L.	1.400
Moment reference center (booster only)	
Dist aft of nose	5.613 inch
W. L.	1.400
C4 CANARD (Basic Canard for B-15B-1 Booster) Drawing No. WT 70-105222	
TOTAL DATA	
Dihedral angle	0.0 degree
Incidence angle	0.0 degree
Aerodynamic twist	0.0 degree
Sweep back angles	
Leading edge	57.7 degree
Trailing edge	0.0 degree
0.25 Element line	53.9 degree
Airfoil section	
Root	0014-(6.6)(S)
Tip	0014-(6.6)(S)



Table 3-2. Booster Model Geometry (Cont)

Dimensions	Model Scale
EXPOSED DATA	
Area	0.706 inch ²
Span (equivalent)	1.218 inch
Aspect ratio	1.867
Taper ratio	0.1058
Chords	
Root	1.061 inch
Tip	.099 inch
MAC	0.802 inch
Fus sta of 0.25 MAC	6.725
W. P. of 0.25 MAC	0.175 inch above C _L
B. L. of 0.25 MAC	0.902 inch
W14 WING (Basic Delta Wing with an unswept T. E., A-4 degree twist, and 3-degree dihedral) Drawing Number WT 70-105222	
TOTAL DATA	
Area	
Planform	15.656 inch ²
Span (equivalent)	6.099 inch
Aspect ratio	2.433
Rate of taper	
Taper ratio	0.1061
Dihedral angle	3.0 degree
Incidence angle	2.0 degree
Aerodynamic twist	-4.0 degree
Sweep back angles	
Leading edge	53.0 degree
Trailing edge	0.0 degree
0.25 Element line	44.87 degree
Chords:	
Root (wing sta 0.0)	4.518 inch
Tip (equivalent)	0.479 inch
MAC	3.095 inch
Fus sta of 0.25 MAC	7.3668 inch
Airfoil section	
Root	0010-64 (Mod)
Tip	0010-64 (Mod)



Table 3-2. Booster Model Geometry (Cont)

Dimensions	Model Scale
EXPOSED DATA	
Area	9.684 inch ²
Span (equivalent)	4.725 inch
Aspect ratio	2.306
Taper ratio	0.1323
Chords	
Root	3.620 inch
Tip	0.479 inch
MAC	2.449 inch
Fus sta of 0.25 MAC	8.808 inch
V7 VERTICAL TAIL (Basic tail for the B-15B-1 Booster) Drawing Number: WT 70-105222	
TOTAL DATA	
Sweep back angles	
Leading edge	35.0 degree
Trailing edge	10.0 degree
EXPOSED DATA	
Area	2.247 inch ²
Span (equivalent)	1.697 inch
Aspect ratio	1.28
Taper ratio	0.50
Chords	
Root	1.764 inch
Tip	0.882 inch
MAC	1.358 inch
Fus sta of .25 MAC	12.408
W.P. of 0.25 MAC	0.0

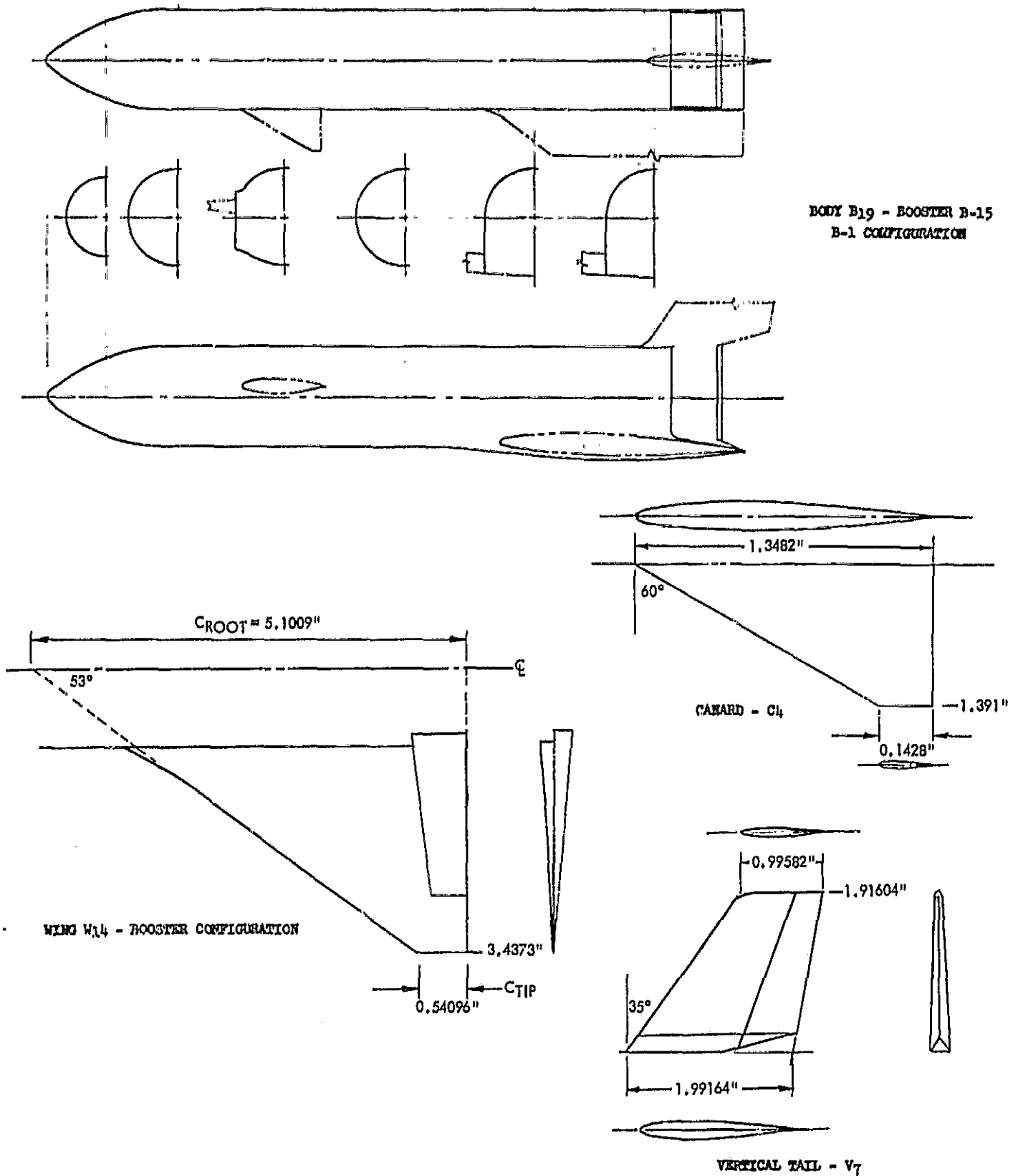
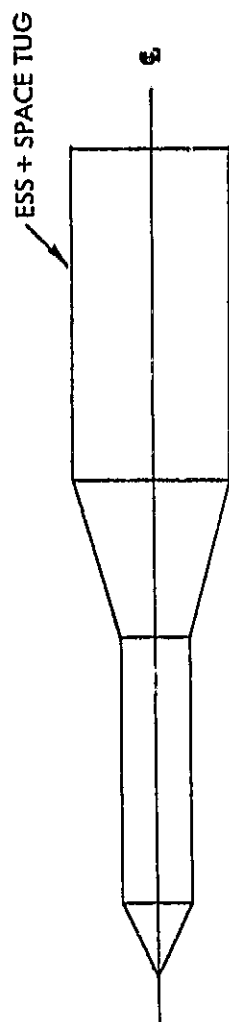


Figure 3-2. Booster Model Geometry



ESS + NUCLEAR PAYLOAD CONFIGURATION

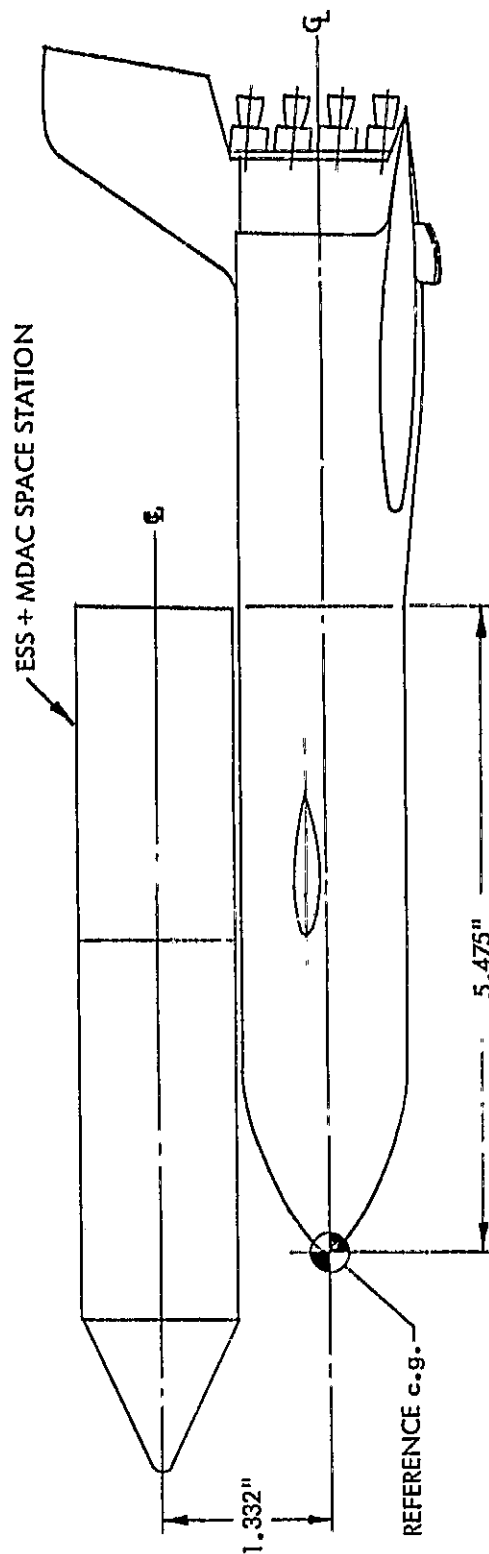
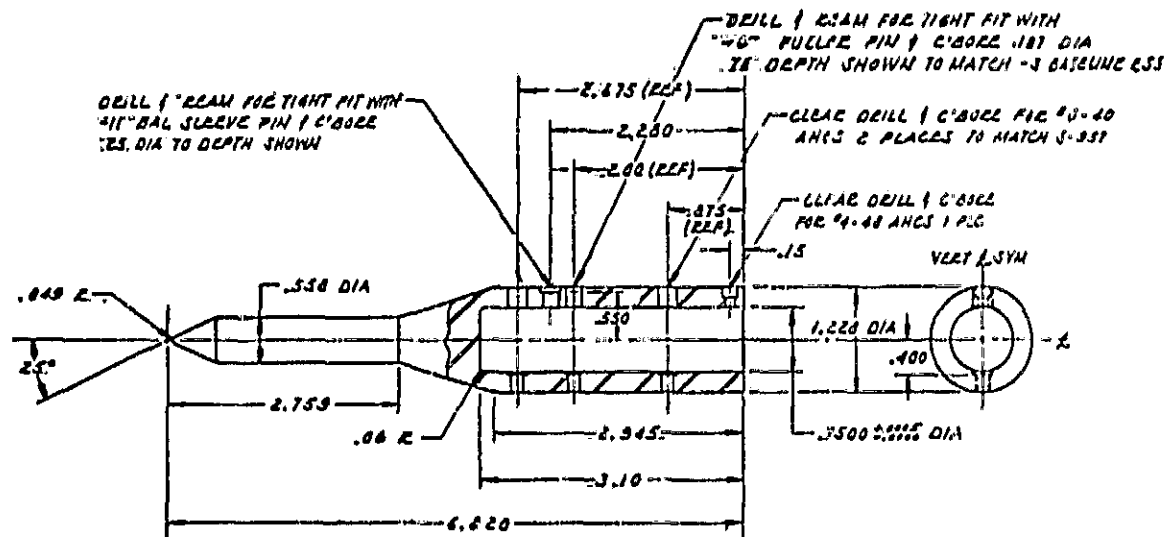
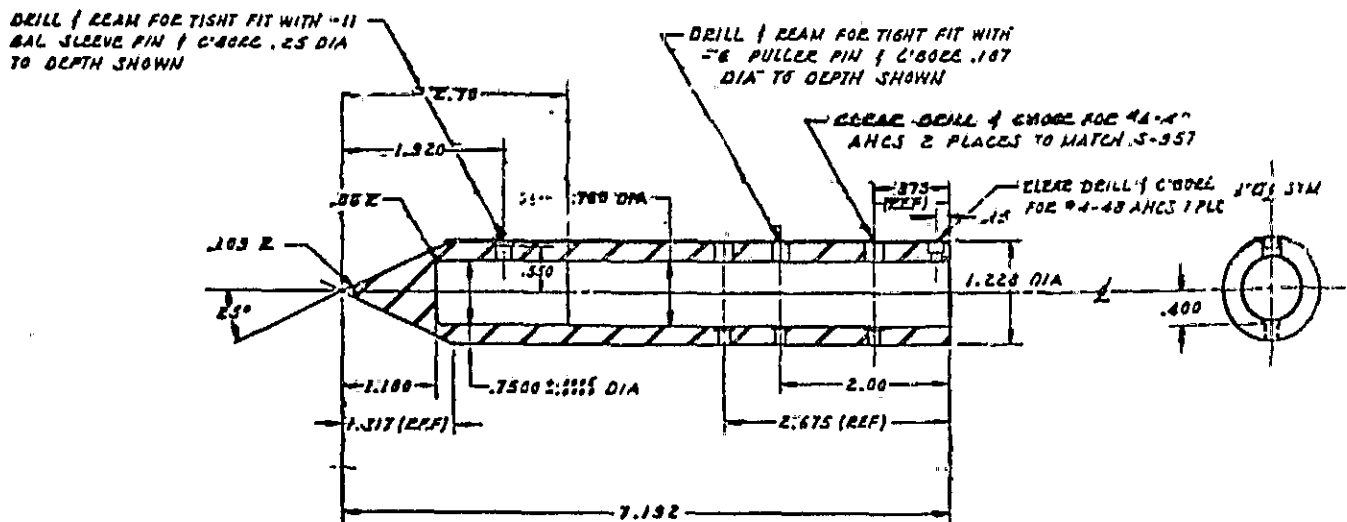


Figure 3-3. ESS Launch Configuration



DETAIL -4 ALTERNATE ESS 1 REQD
MAT'L: ARMCO 17-4 PH CEES

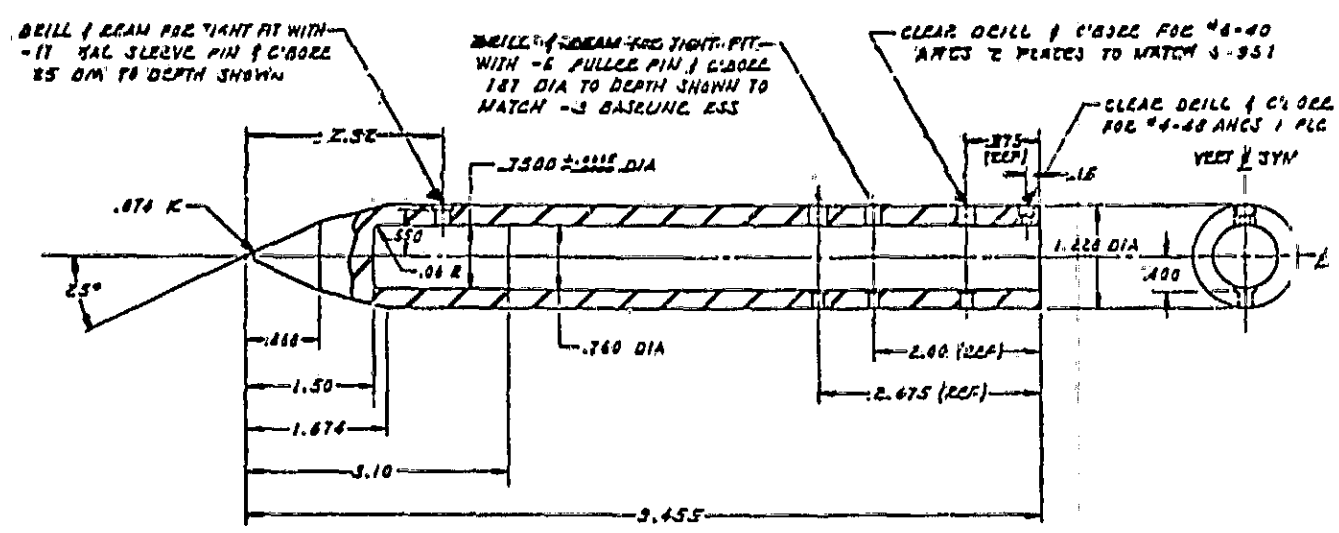
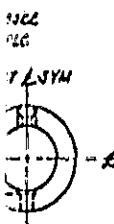


DETAIL -3 BASELINE ESS 1 REQD
MAT'L: ARMCO 17-4 PH CEES

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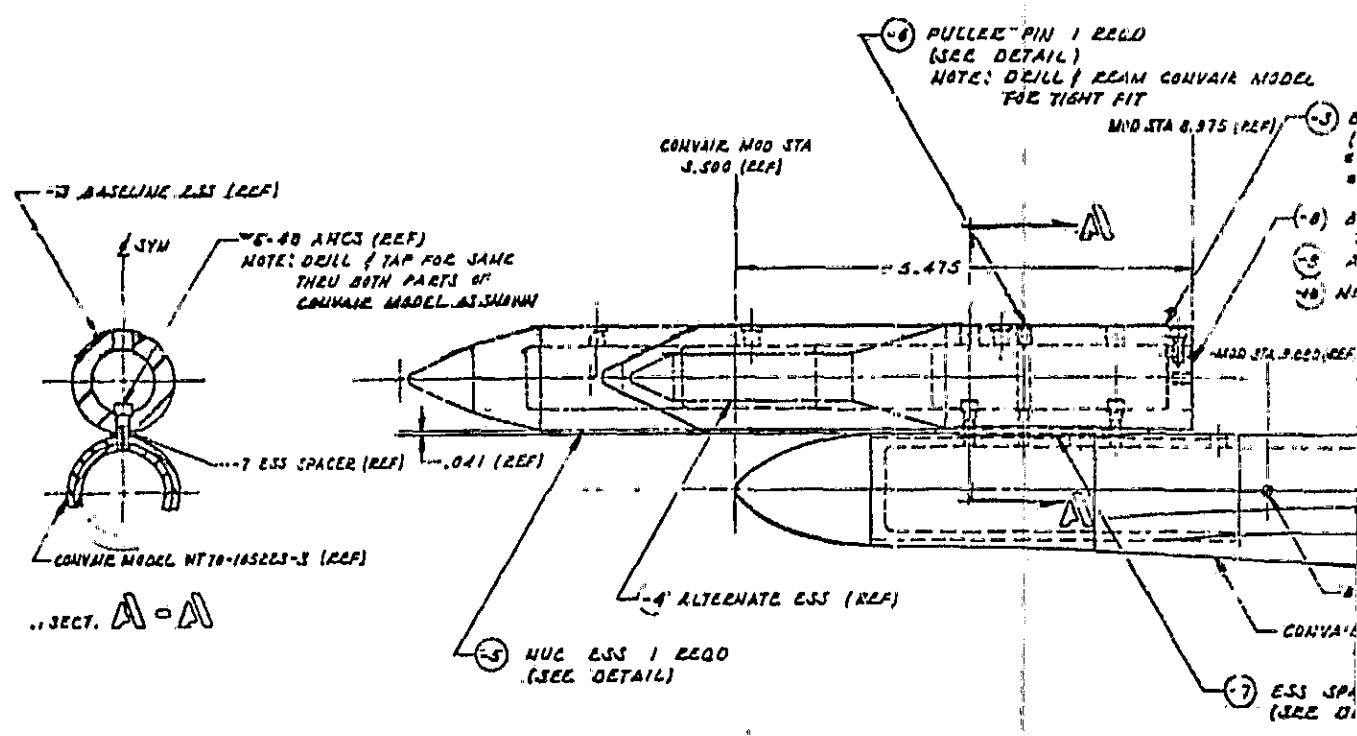
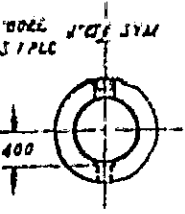
T FIT WITH
HOLE .187 DIA
MATCH -3 BASELINE ESS

HOLE FOR #3-40
TO MATCH S-951



DETAIL -3 HUC ESS 1 REQD
MAT'L: ARMCO 17-4 PH CRES

HOLE .187 DIA
MATCH -3 BASELINE ESS



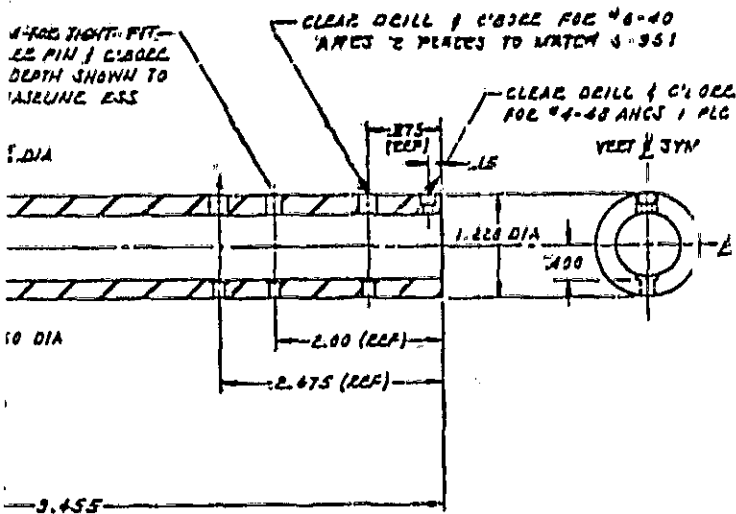
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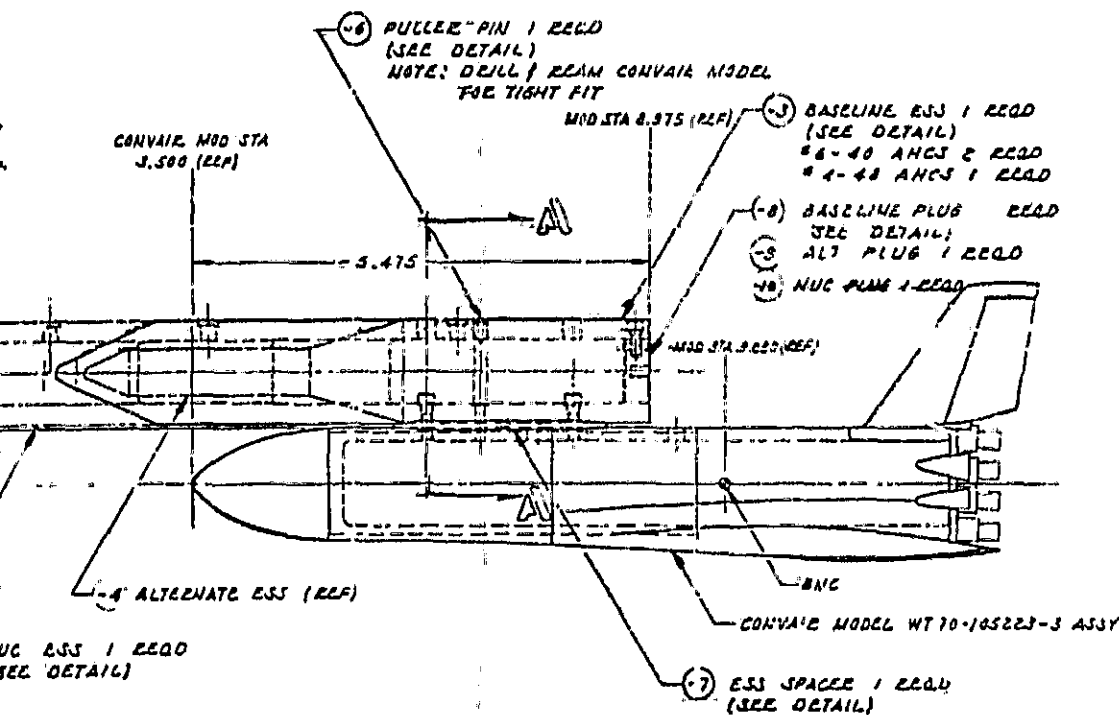
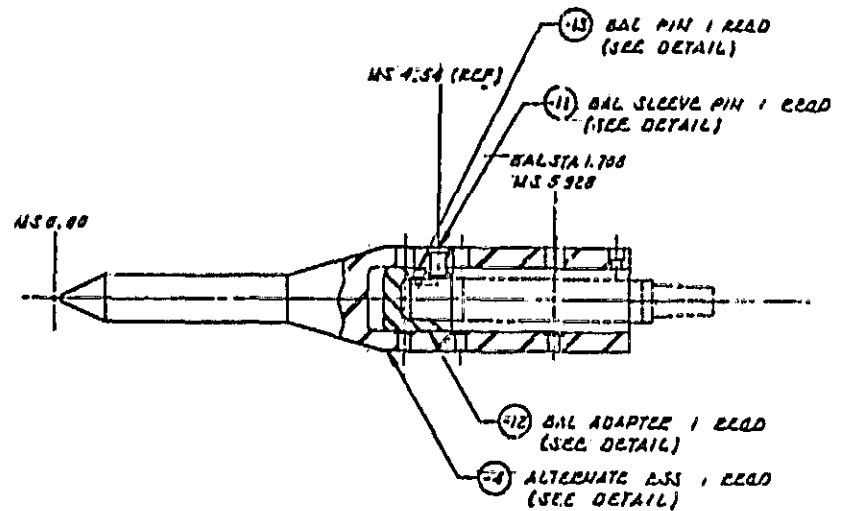
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DETAIL -2 MODEL ASSY 1 REQD
MAT'L: NOTED

Figure 3-4. Model



1 NUC ESS 1 REQD
UCB 17-4 PH CRES



DETAIL - 2 MODEL ASSY 1 REQD
MAT'L: NOTED

FOLDOUT FRAME

3

Figure 3-4. Model Drawings for ESS Launch Configurations



4.0 AERODYNAMIC CHARACTERISTICS

4.1 LONGITUDINAL CHARACTERISTICS

Launch configuration forebody axial force coefficients were obtained by applying measured booster base and sting cavity pressures to the respective areas and subtracting from the total measured axial force. Therefore, as defined, forebody axial force for the launch vehicles includes the ESS power-off base drag as measured in the test. Figure 4-1 shows a comparison of forebody axial force coefficient for the three launch vehicles. Supersonically the ESS/MDAC plus booster has the largest axial force and averages approximately 14 percent higher than the ESS/RNS plus booster and 7 percent higher than the ESS/ST and booster.

Normal force characteristics presented in Figures 4-2 and 4-3 show a general decrease in the normal force intercept $C_{N(\alpha=0)}$ with decreasing overhang of the ESS/payload noses relative to the booster nose (viz, ESS/RNS to ESS/MDAC to ESS/ST). This trend was consistent over the Mach range tested. A similar trend is exhibited in the normal force slope. However, it varies with Mach number, becoming more pronounced with increasing Mach number. The comparison of zero angle-of-attack pitching moment coefficients in Figure 4-4 shows the largest sensitivity to configuration occurring transonically and decreasing with increasing Mach number. Figure 4-5 shows a reverse trend in the pitch aerodynamic center with less sensitivity to configuration occurring transonically and increasing with Mach number. To provide static pitch stability over the Mach number range $0 \leq M \leq 5.0$, extrapolation of the data indicates center-of-gravity locations of 48, 54, and 58 percent of booster length for the RNS, MDAC and space tug payloads, respectively.

4.2 LATERAL-DIRECTIONAL CHARACTERISTICS

The yaw aerodynamic centers for the three launch configurations are shown in Figure 4-6. Yaw stability generally is 12 to 14 percent of booster length less than pitch stability and would require center of gravities to be moved forward by these percentages to maintain comparable yaw stability. Figures 4-7 through 4-9 present side force yawing and rolling moment slope coefficients respectively for the ESS/MDAC and booster configuration at zero and -6 degrees angle of attack. The angle-of-attack effect shows an increase in side force of approximately 5 percent from $\alpha = 0$ to $\alpha = -6$ degrees and an increase in rolling moment of approximately 35 percent for



the same α range. Yaw stability increases below $M = 2.2$ and decreases slightly above $M = 2.2$ with negative angle of attack.

Figures 4-10 through 4-12 compare the three configurations at an angle of attack of $\alpha = -6$ degrees. Side force exhibits minor difference with configuration. The MDAC and RNS payload configurations show comparable yaw stability, but are less stable than the space tug payload configuration. Roll due to yaw is least for the space tug and increases significantly for the MDAC and RNS payload configurations.

Booster rudder control effectiveness is presented in Figure 4-13 for the ESS/MDAC and booster configuration at angles of attack of $\alpha = 0$ and $\alpha = -6$ degrees. The data show a reduction in the yawing moment with negative angle of attack as compared to $\alpha = 0$ degrees.

Booster elevon control effectiveness is presented in Figure 4-14 and shows a rapid reduction with increased Mach number for the Mach range tested.

Figures 4-15 and 4-16 show the incremental increase in axial force coefficients with control surface deflections. From these data it can be seen that transonically ($M \approx 1.2$) large drag increases will be effected with large control deflections. For example at $M = 1.2$ elevon deflections of 40 degrees differential increases the forebody axial force by 18 percent and 60 degrees differential deflection increases the forebody axial force by 31 percent.

Figures 4-17 through 4-19 present respectively the axial force, normal force, and stability characteristics of the isolated ESS plus payload stages. Since these configurations are symmetrical bodies of revolution the pitch plane data are interchangeable to the yaw plane (i. e., $C_{N\alpha} = C_{Y\beta}$ and pitch ac = yaw ac).

The basic wind tunnel data used in the analysis are presented in Static Aerodynamic Stability and Control Investigation of An Expendable Second Stage With Payload Alone and With A Delta Wing Booster (B-15 B-1), DMS-DR1119, June 1971. Isolated booster aerodynamic characteristics can be obtained from Longitudinal and Lateral Aerodynamic Characteristics of The 0.0035 Scale GDC Aerospace Booster (B-15 B-1), DMS-DR1102, June 1971.

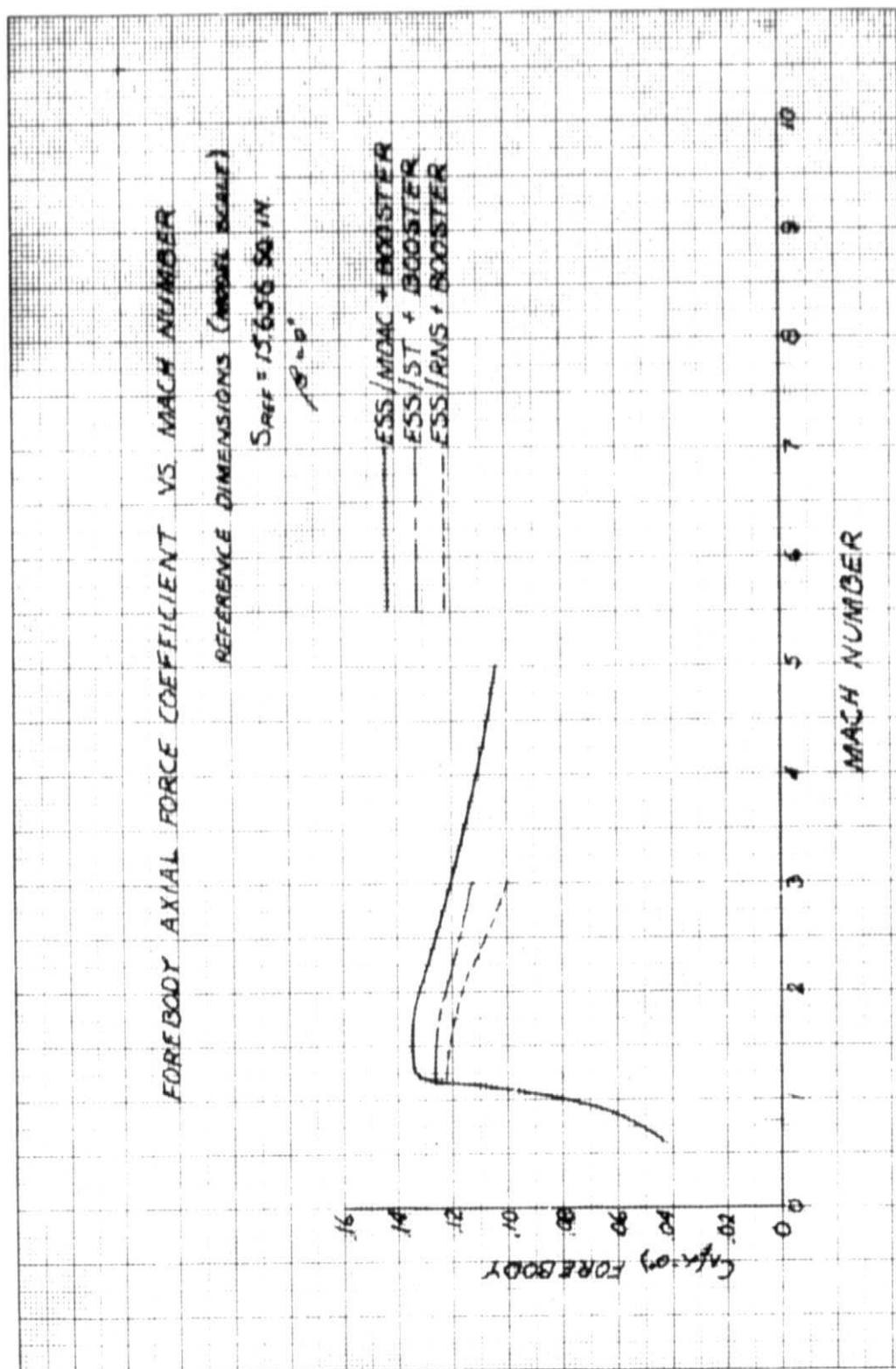


Figure 4-1. Axial Force Characteristics

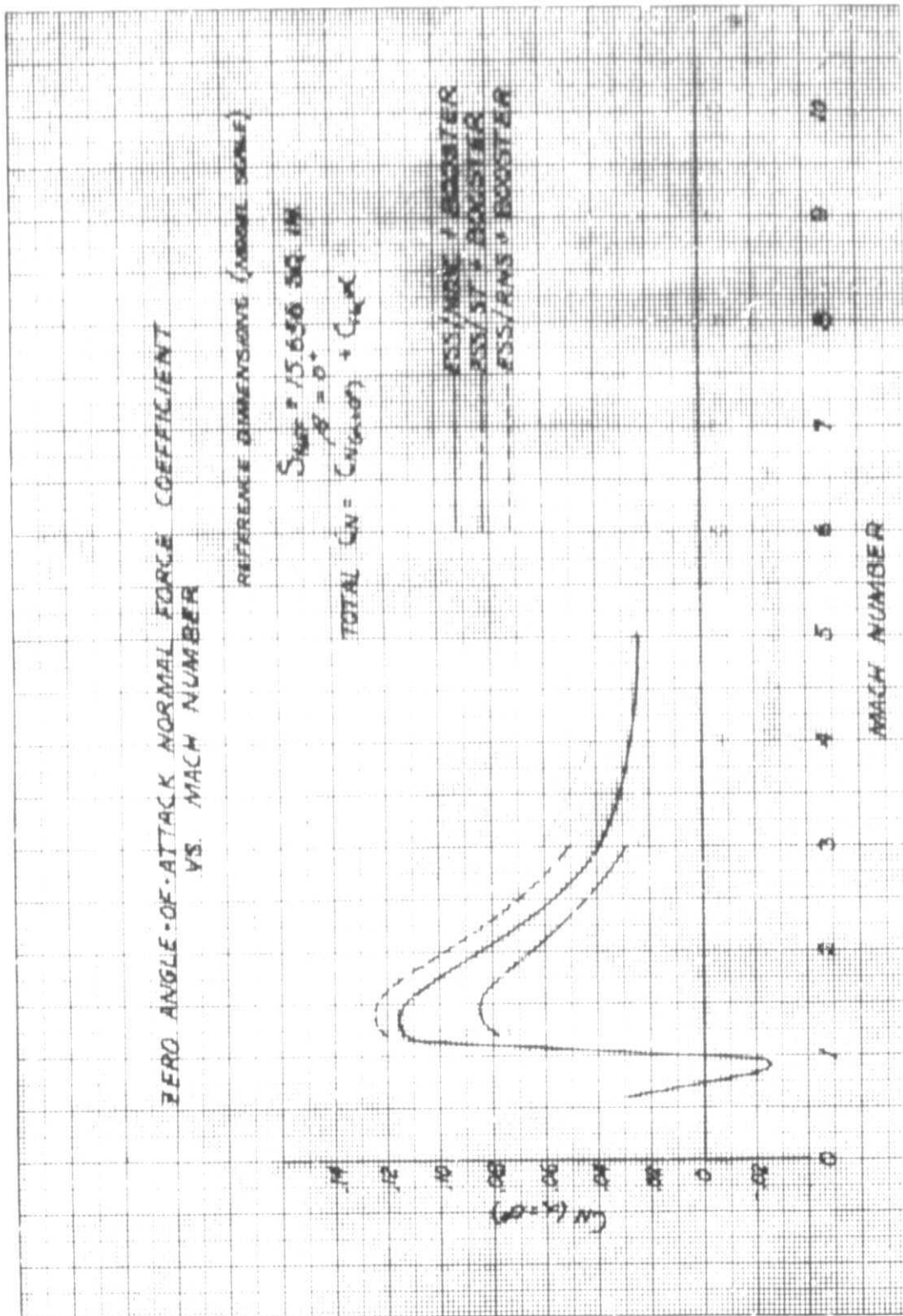


Figure 4-2. Normal Force Intercept

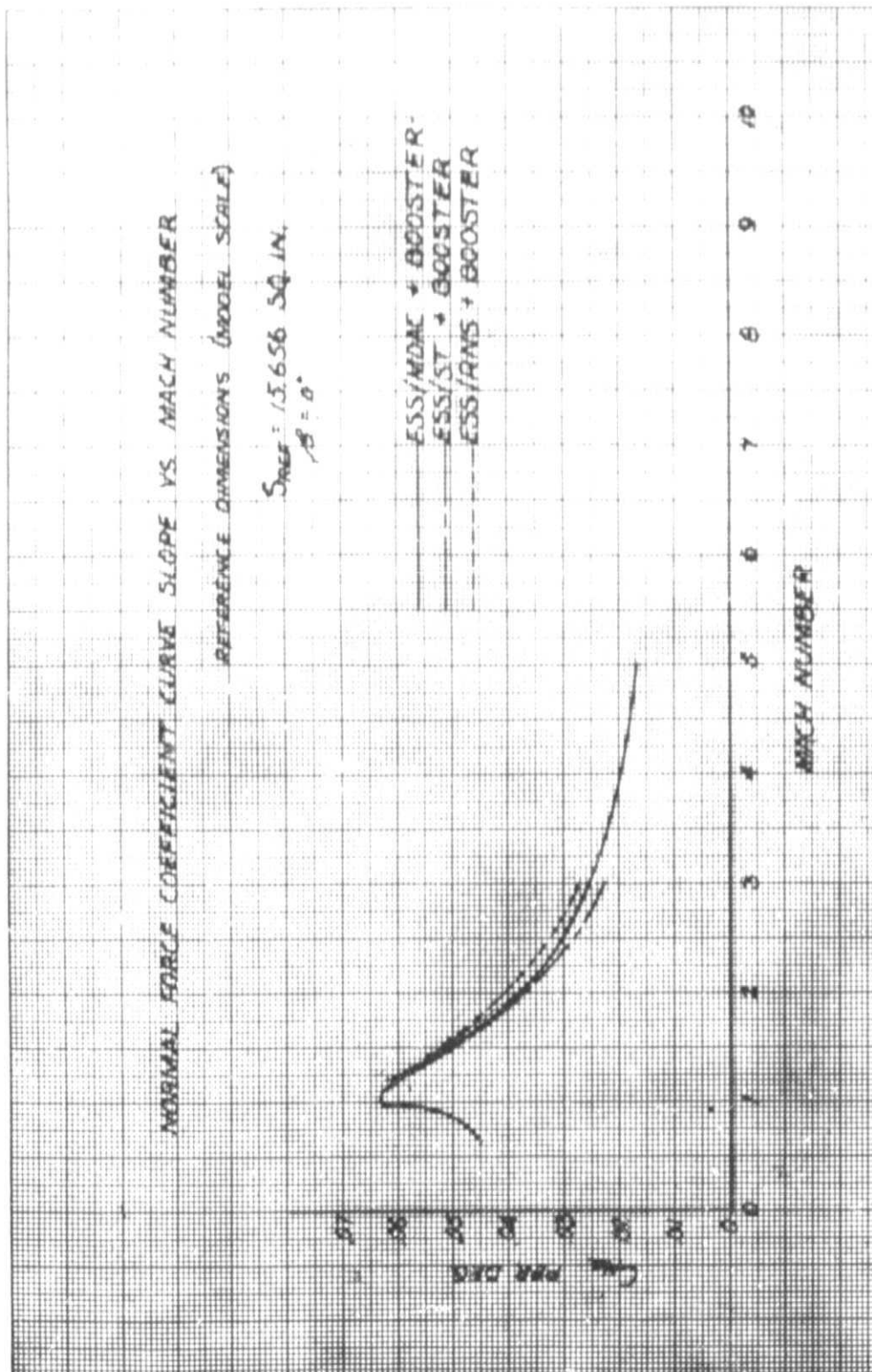


Figure 4-3. Normal Force Characteristics

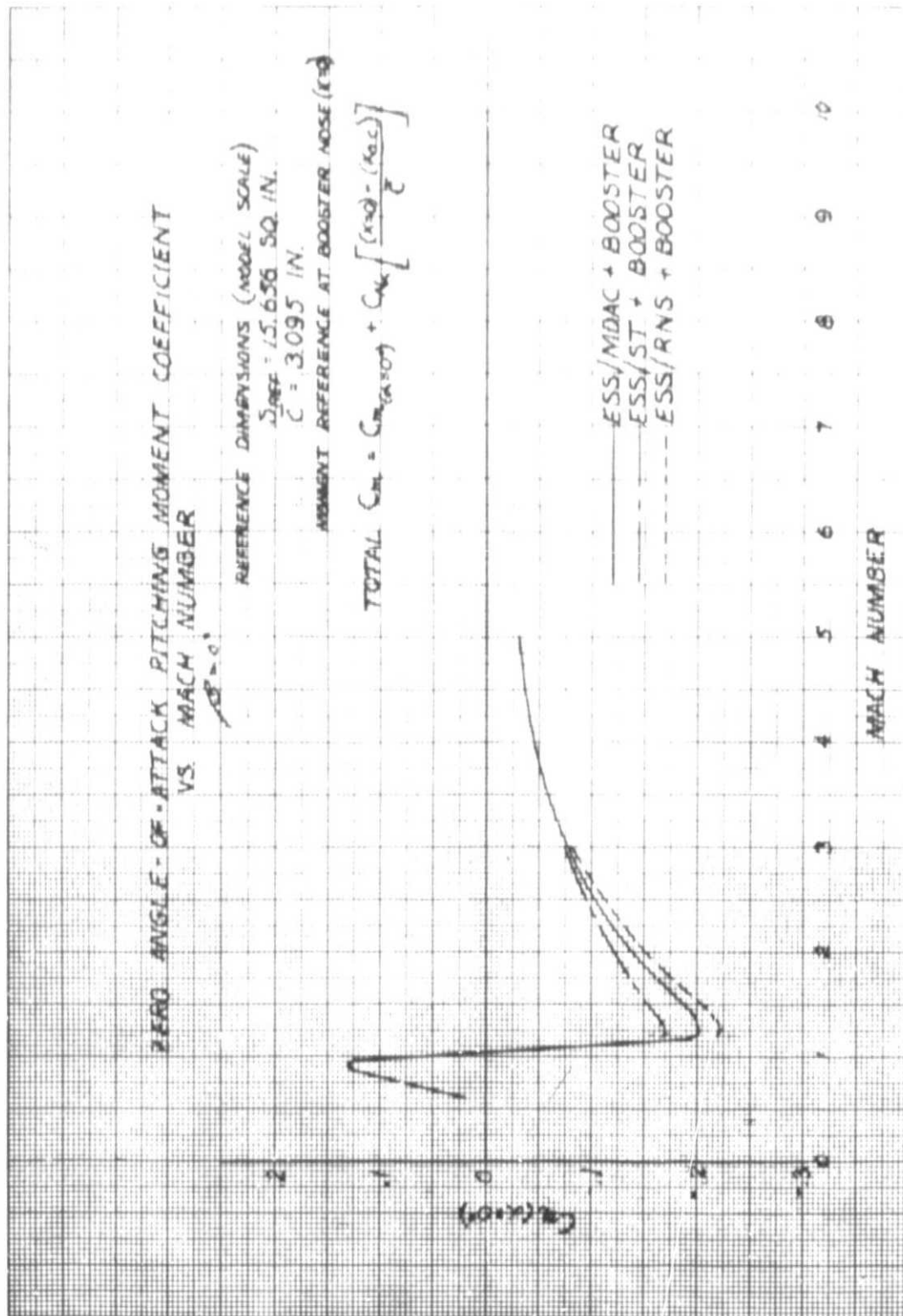


Figure 4-4. Pitching Moment Characteristics

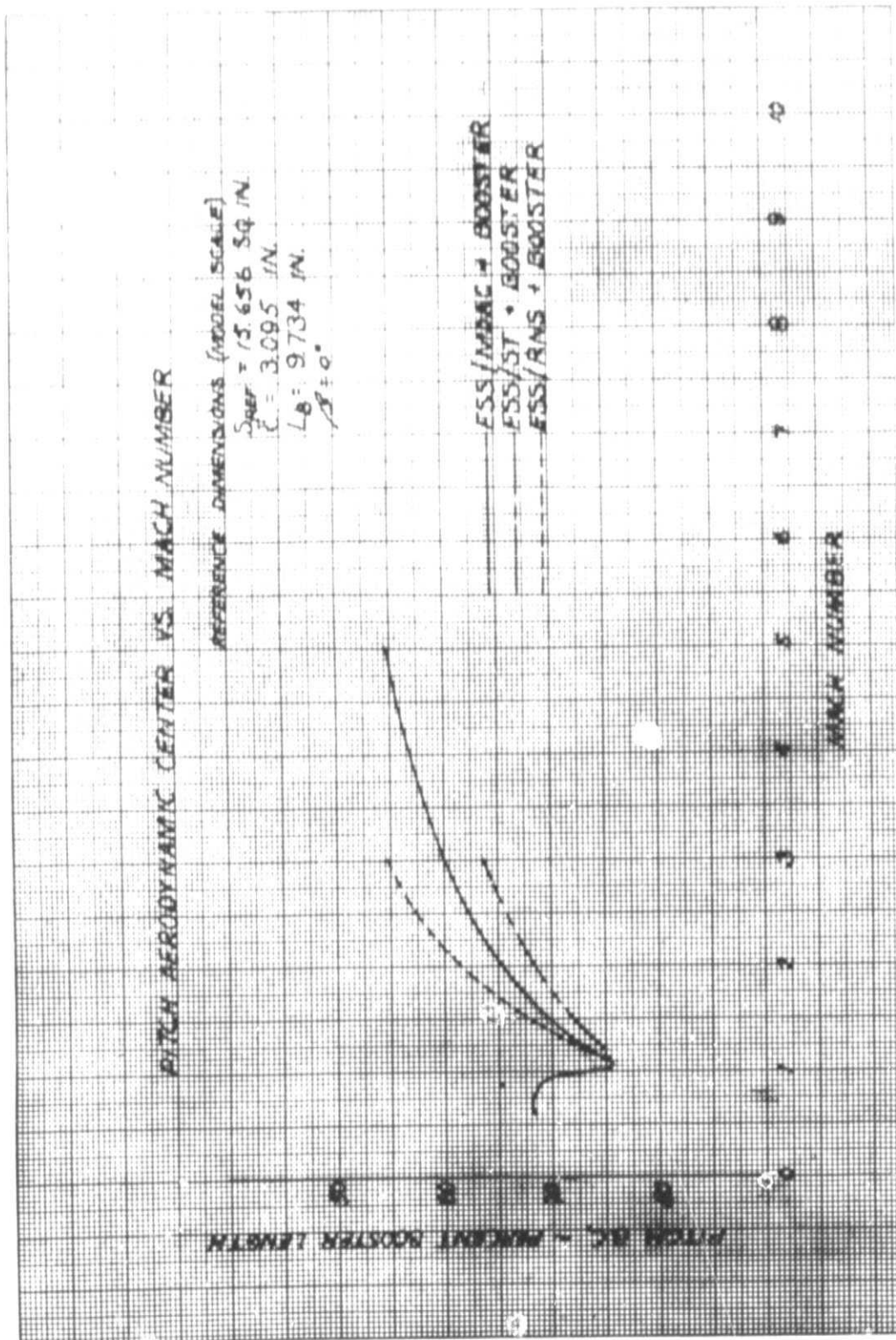


Figure 4-5. Pitch Stability Characteristics

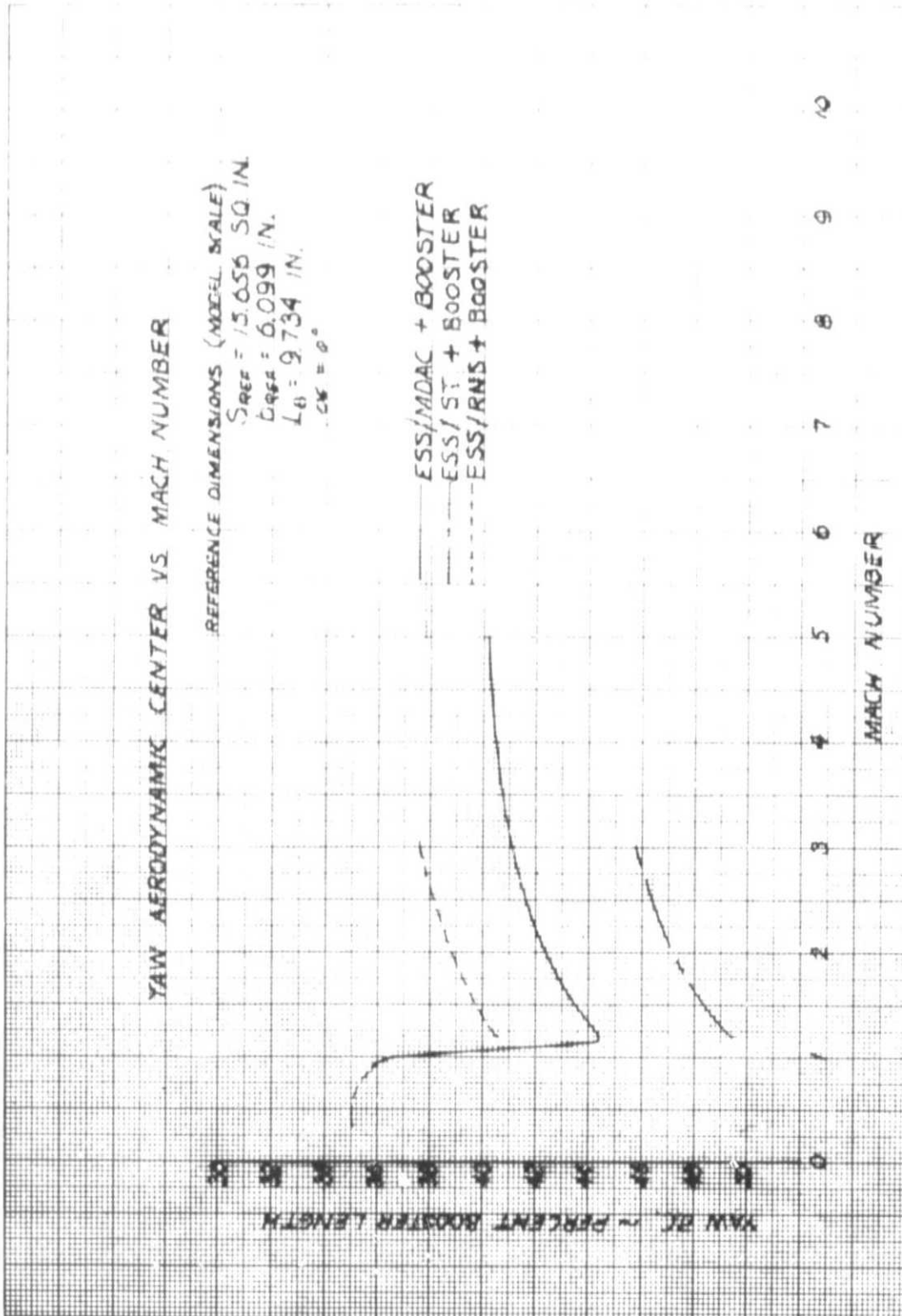


Figure 4-6. Yaw Stability Characteristics

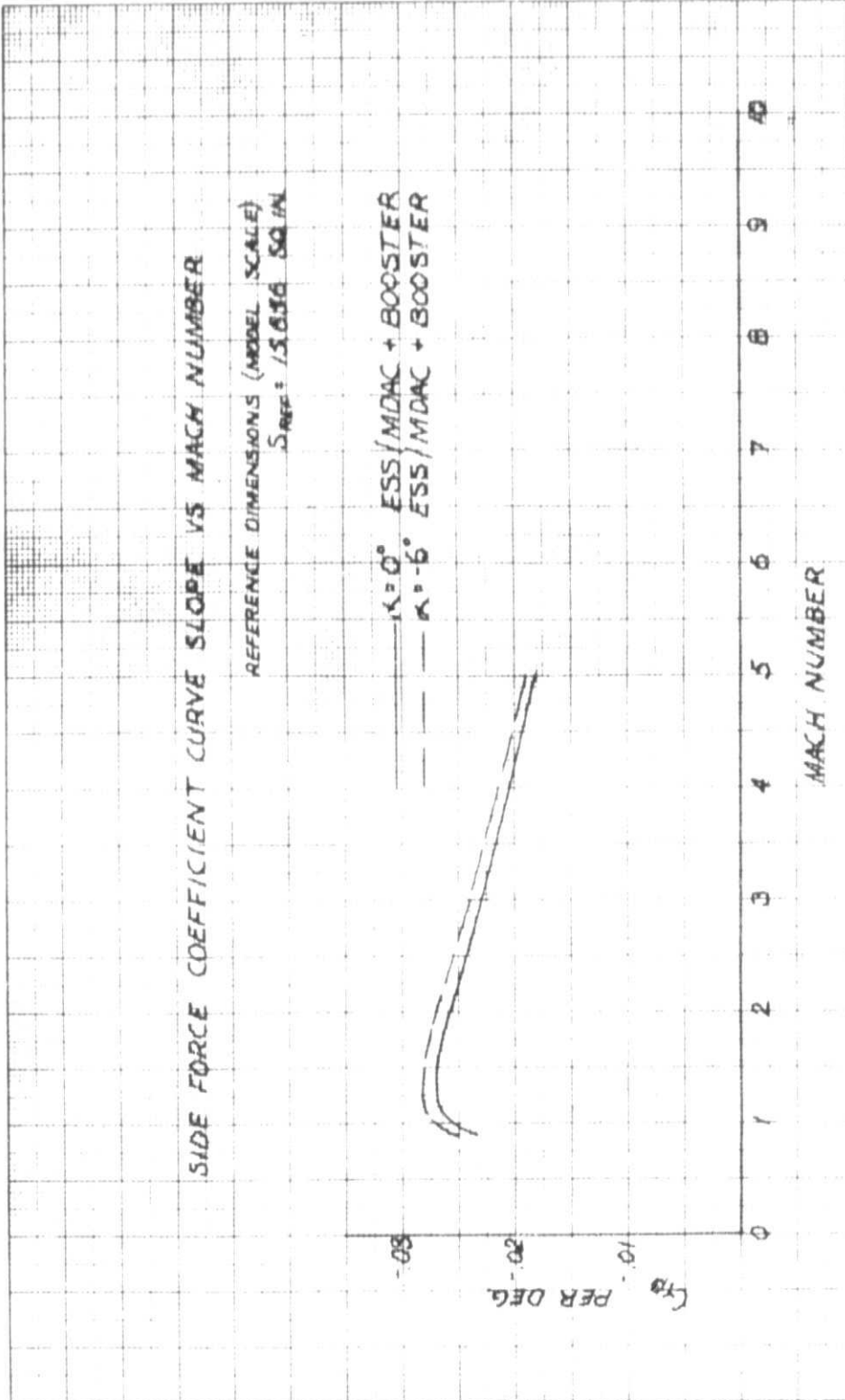


Figure 4-7. Side Force Characteristics (α Effect)

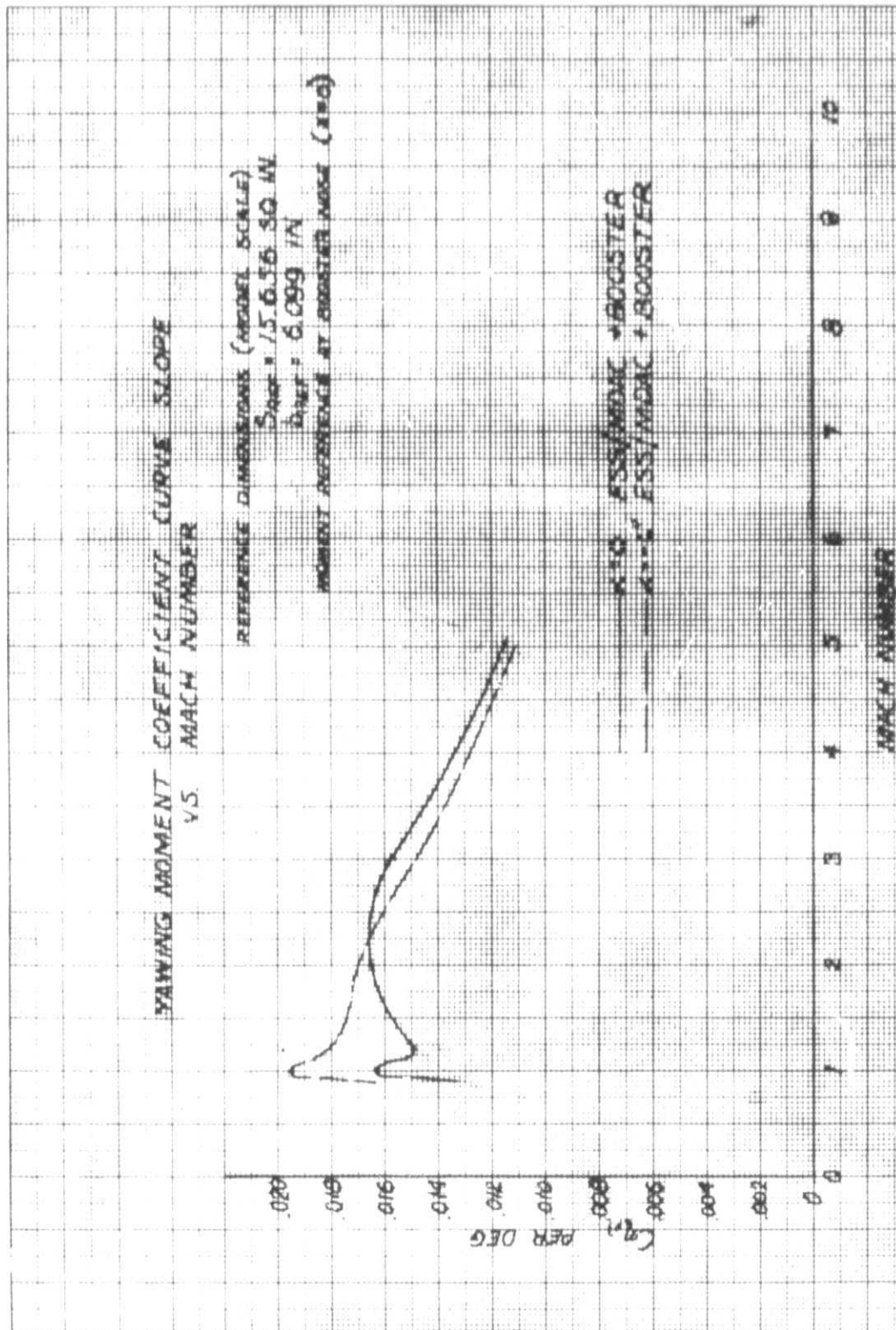


Figure 4-8. Yawing Moment Characteristics

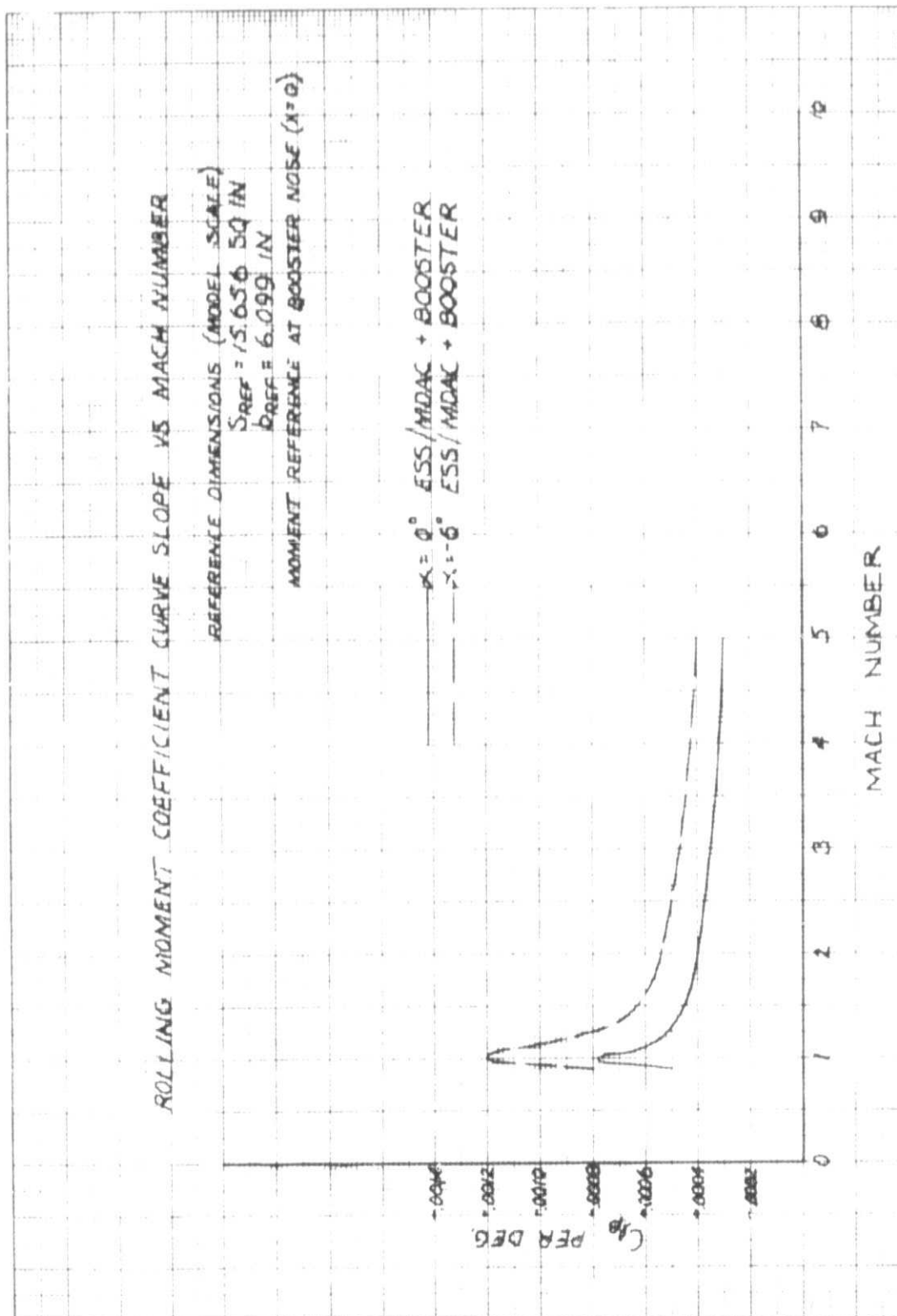


Figure 4-9. Rolling Moment Characteristics

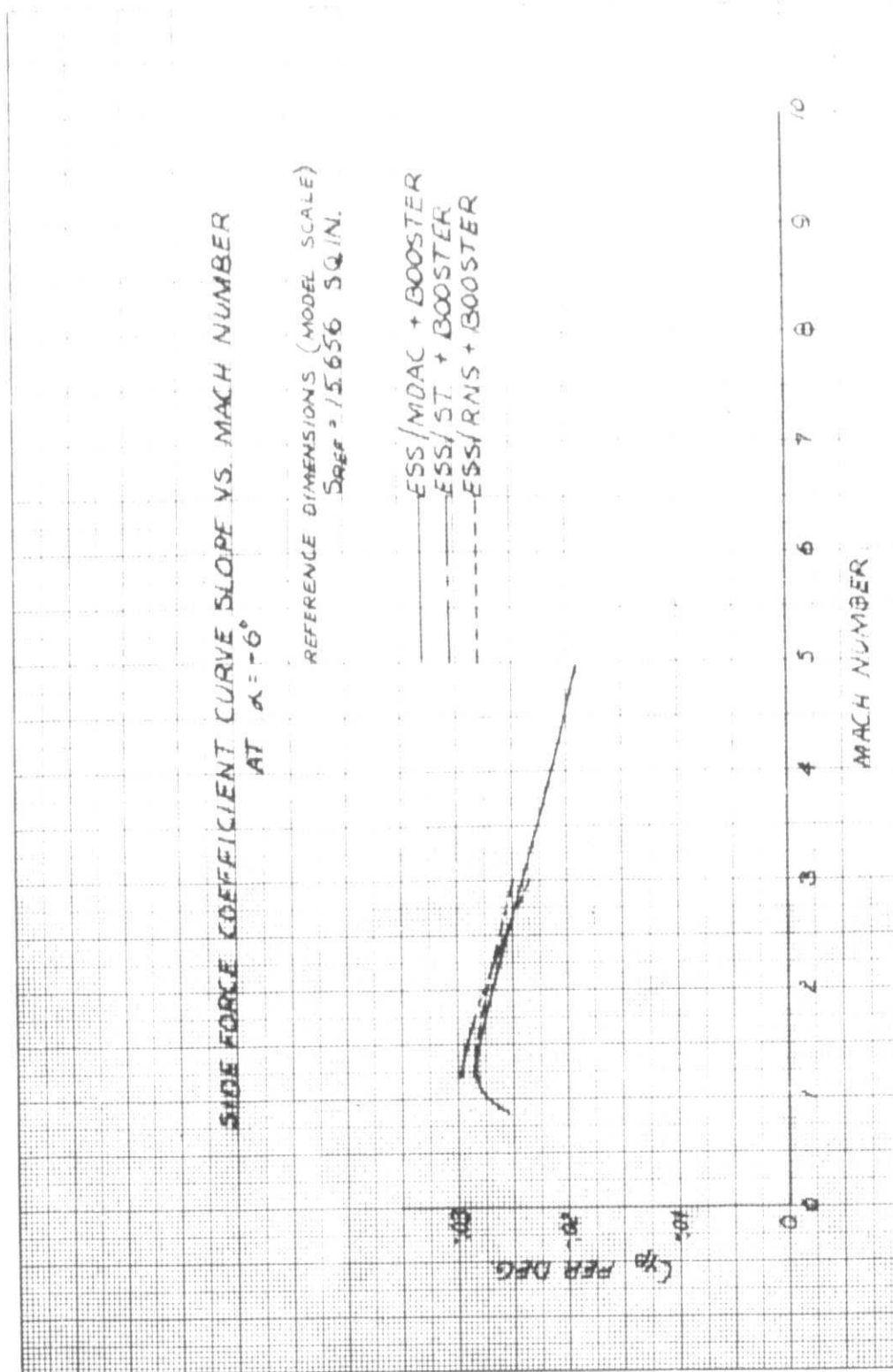


Figure 4-10. Side Force Characteristics at $\alpha = -6$ Degrees

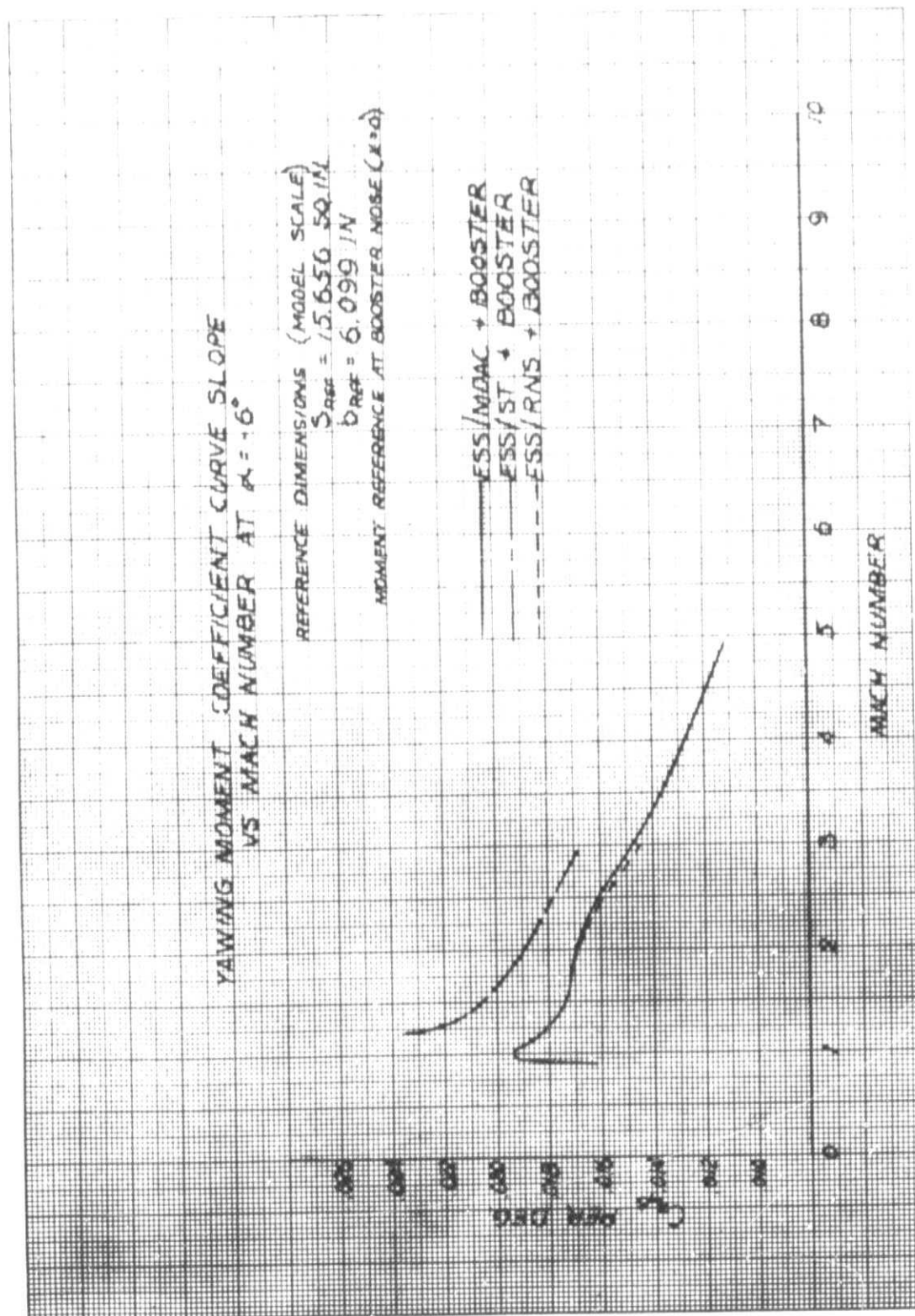


Figure 4-11. Yawing Moment Characteristics at $\alpha = -6$ Degrees

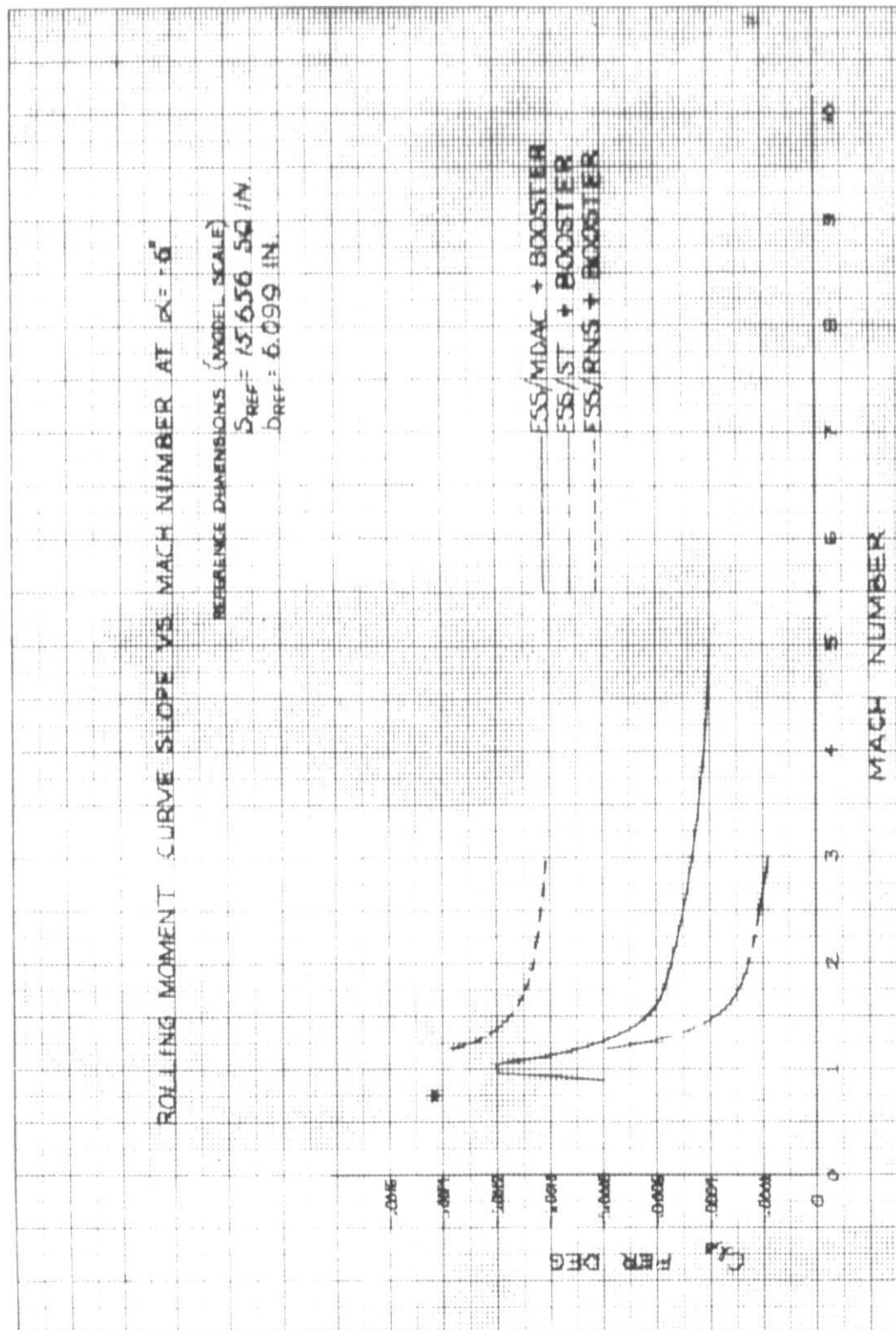


Figure 4-12. Rolling Moment Characteristics at $\alpha = -6$ Degrees

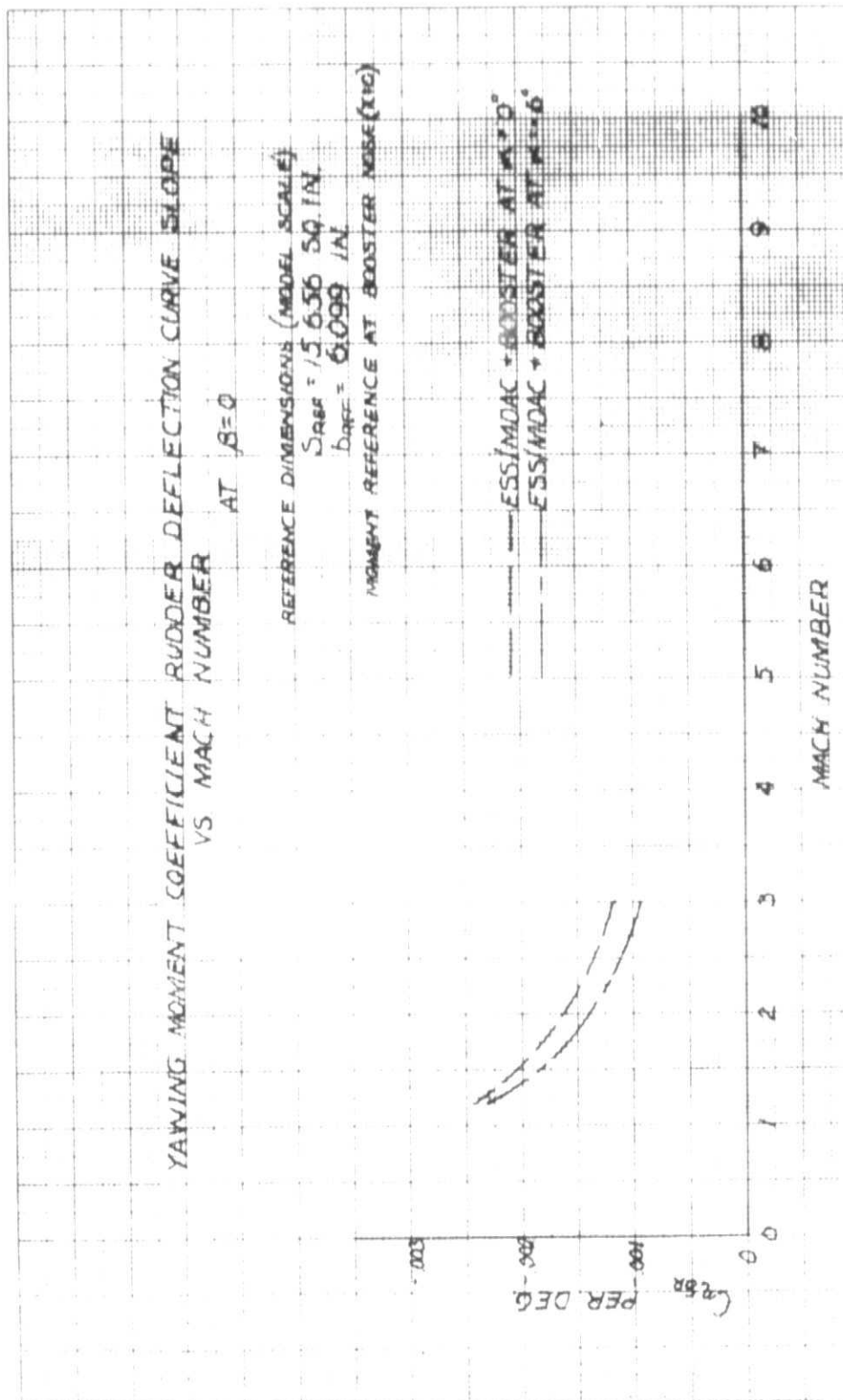


Figure 4-13. Booster Rudder Effectiveness

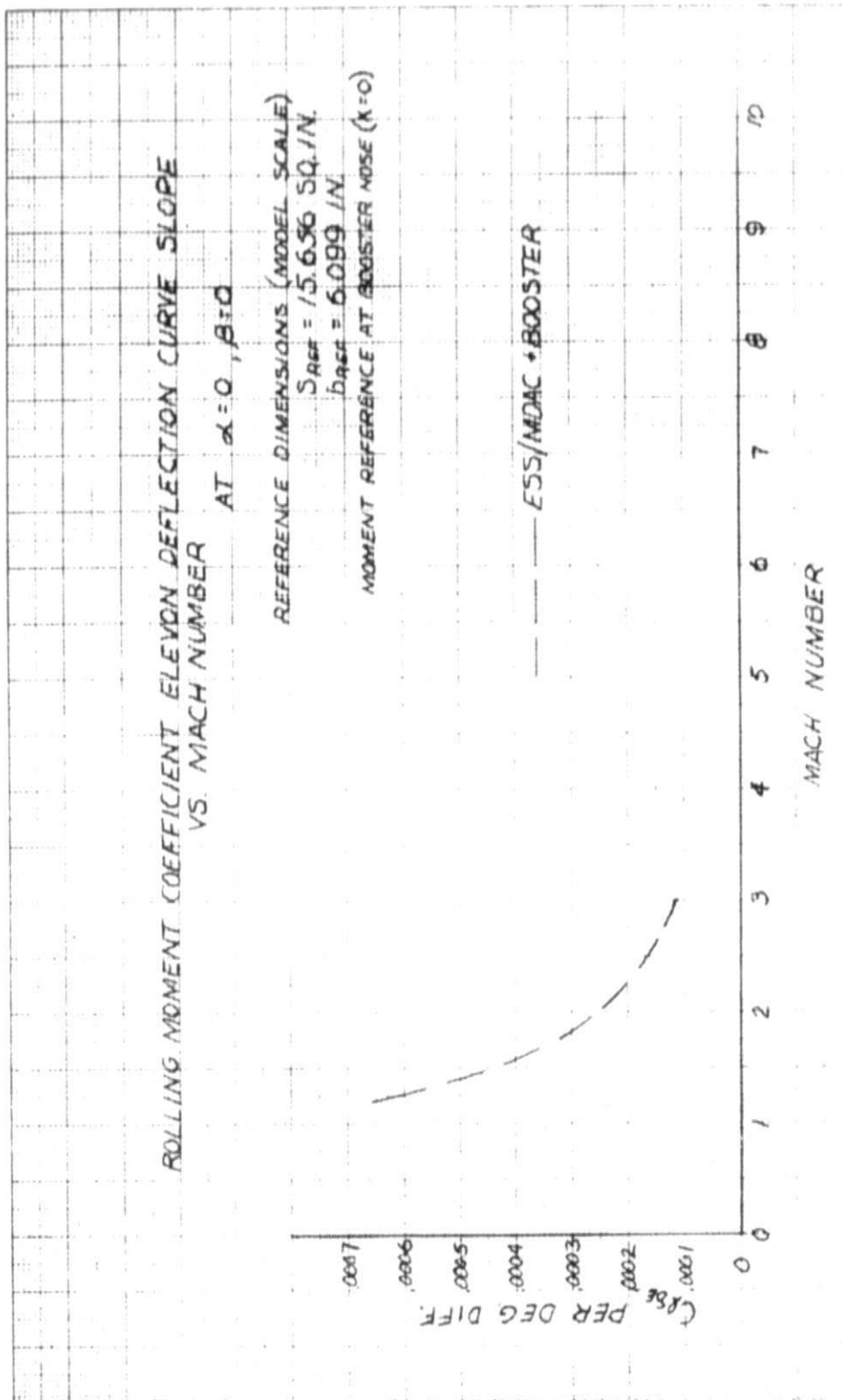


Figure 4-14. Booster Elevon Effectiveness

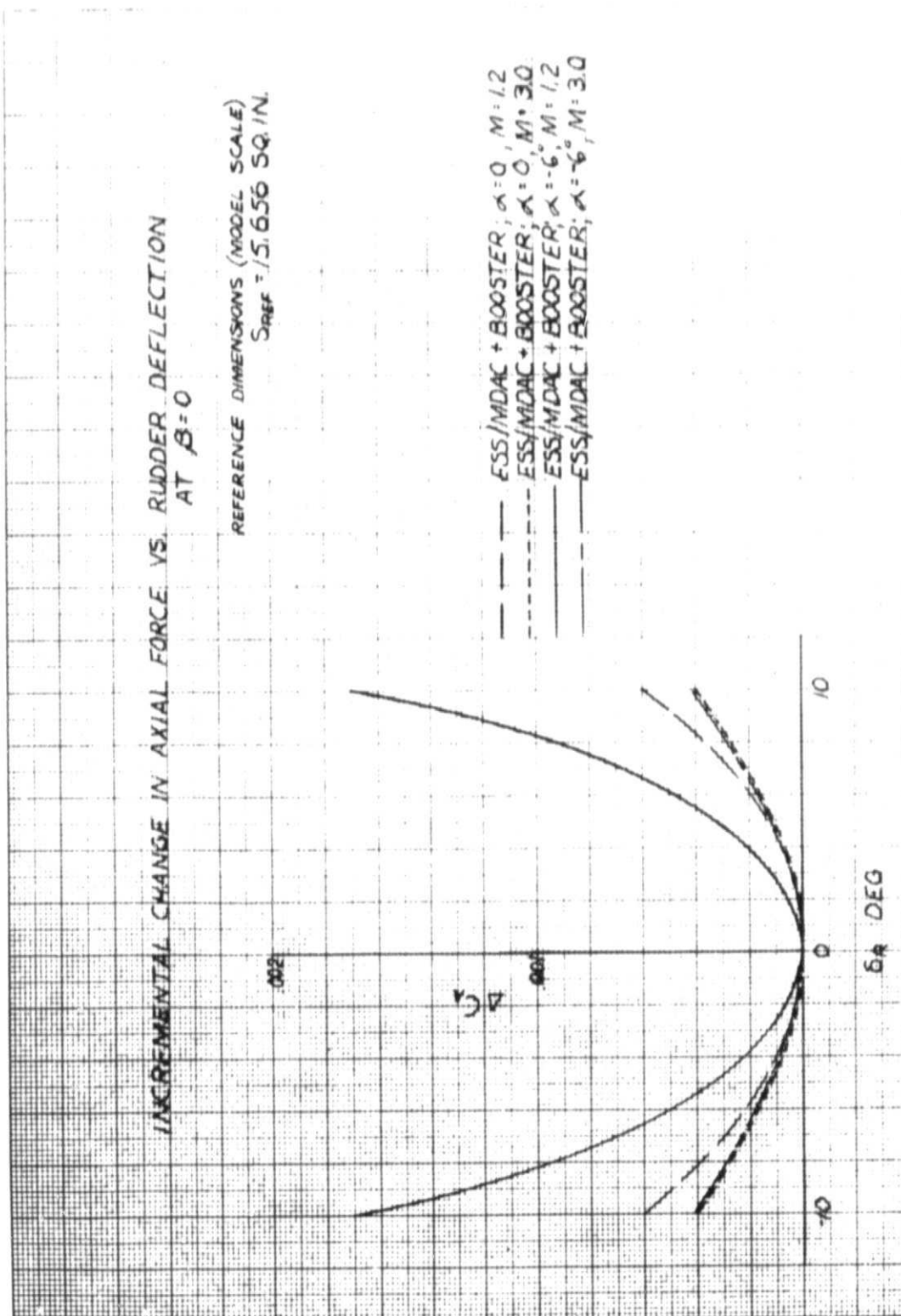


Figure 4-15. Effect of Rudder Deflection on Longitudinal Characteristics

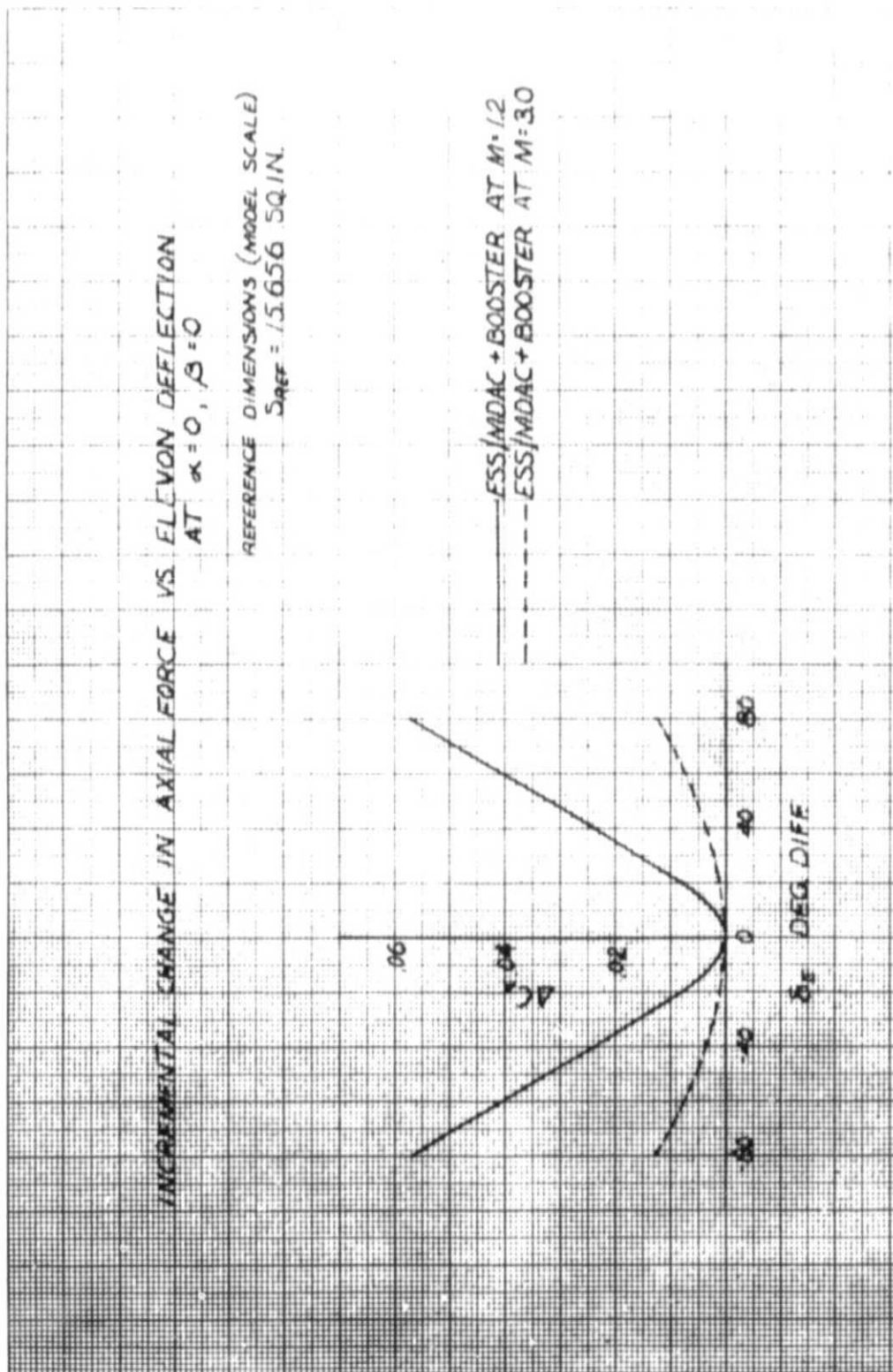


Figure 4-16. Effect of Elevon Deflection on Longitudinal Characteristics

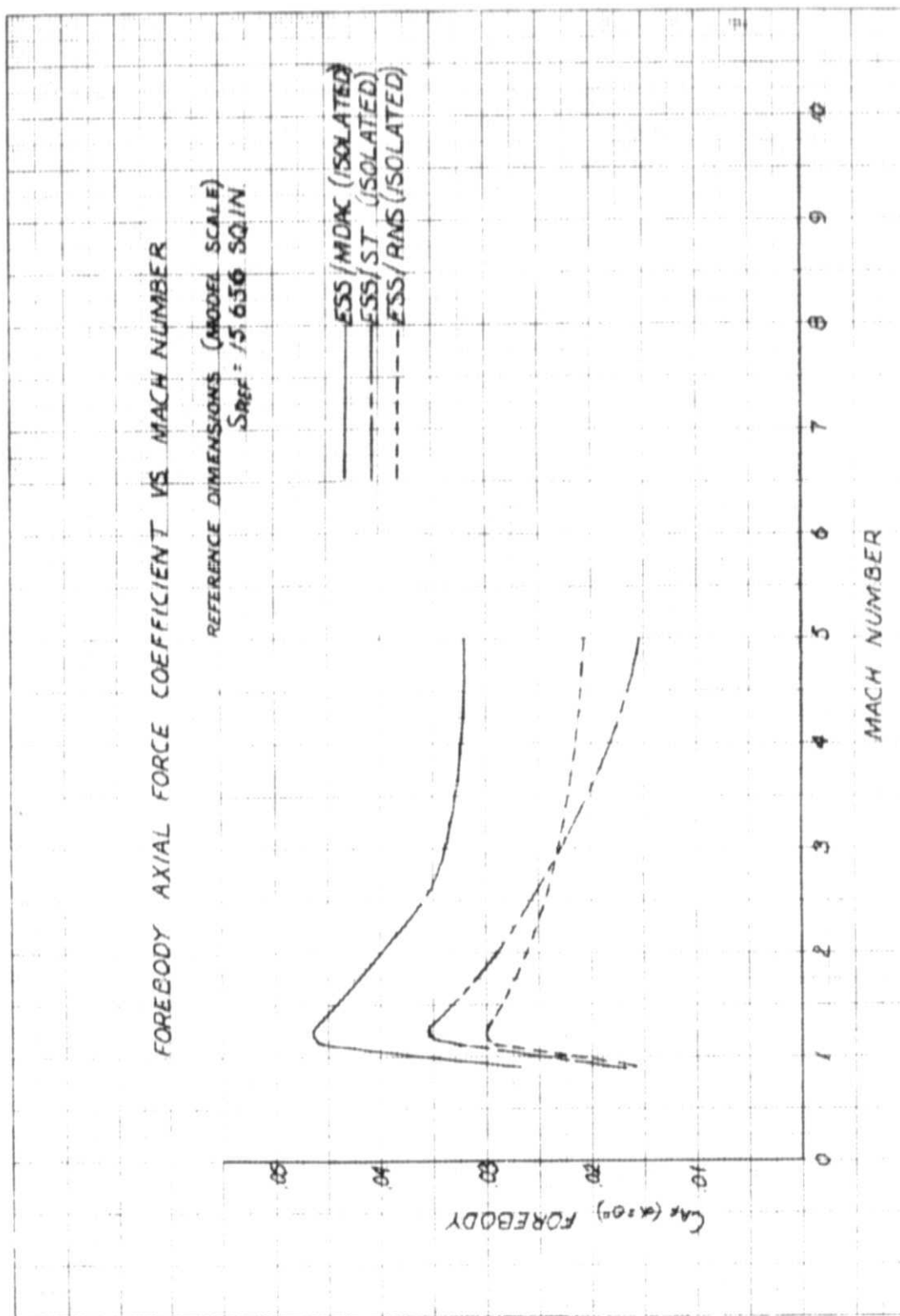


Figure 4-17. Isolated ESS/Payload Axial Force Characteristics

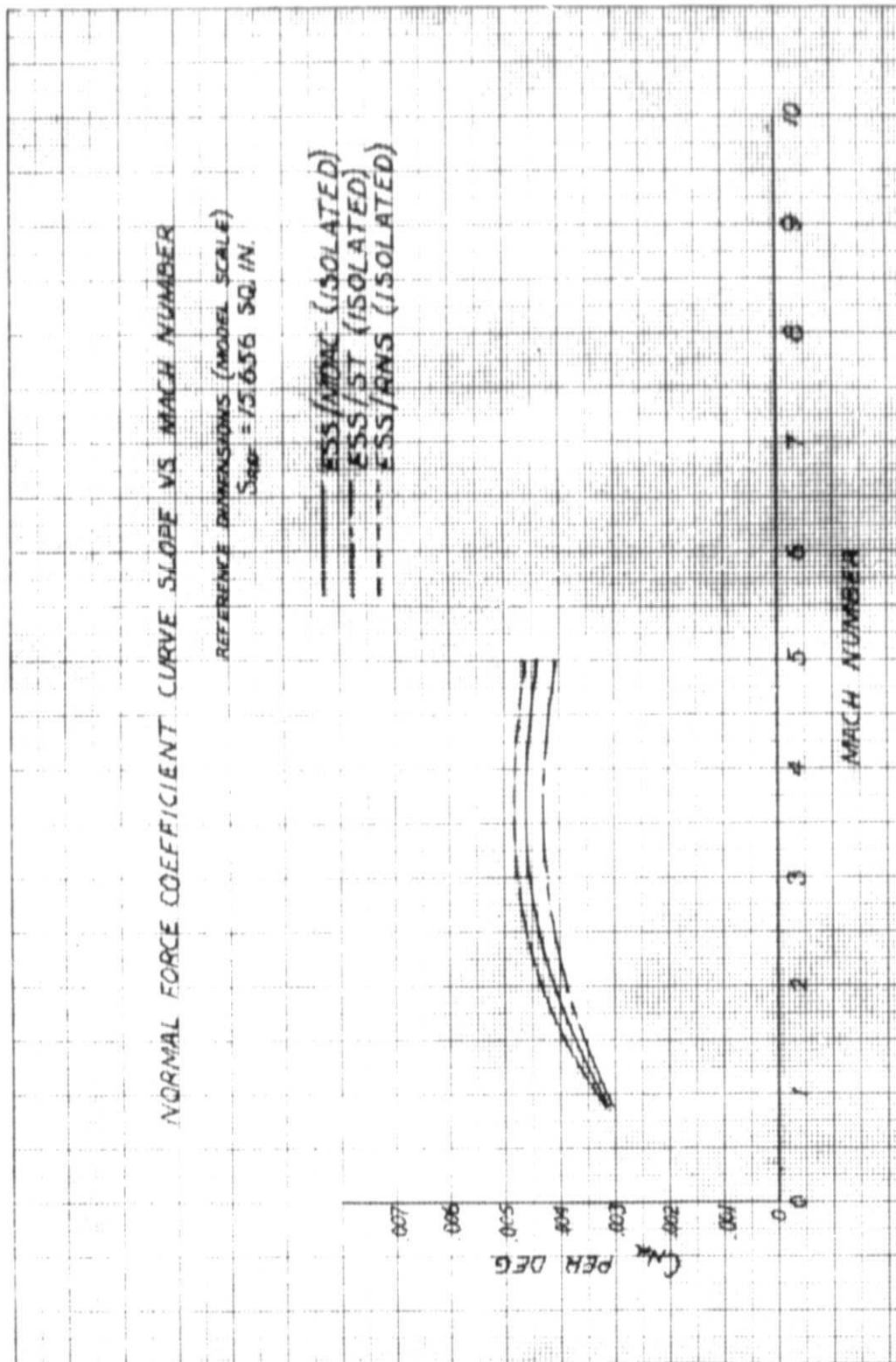


Figure 4-18. Isolated ESS/Payload Normal Force Characteristics

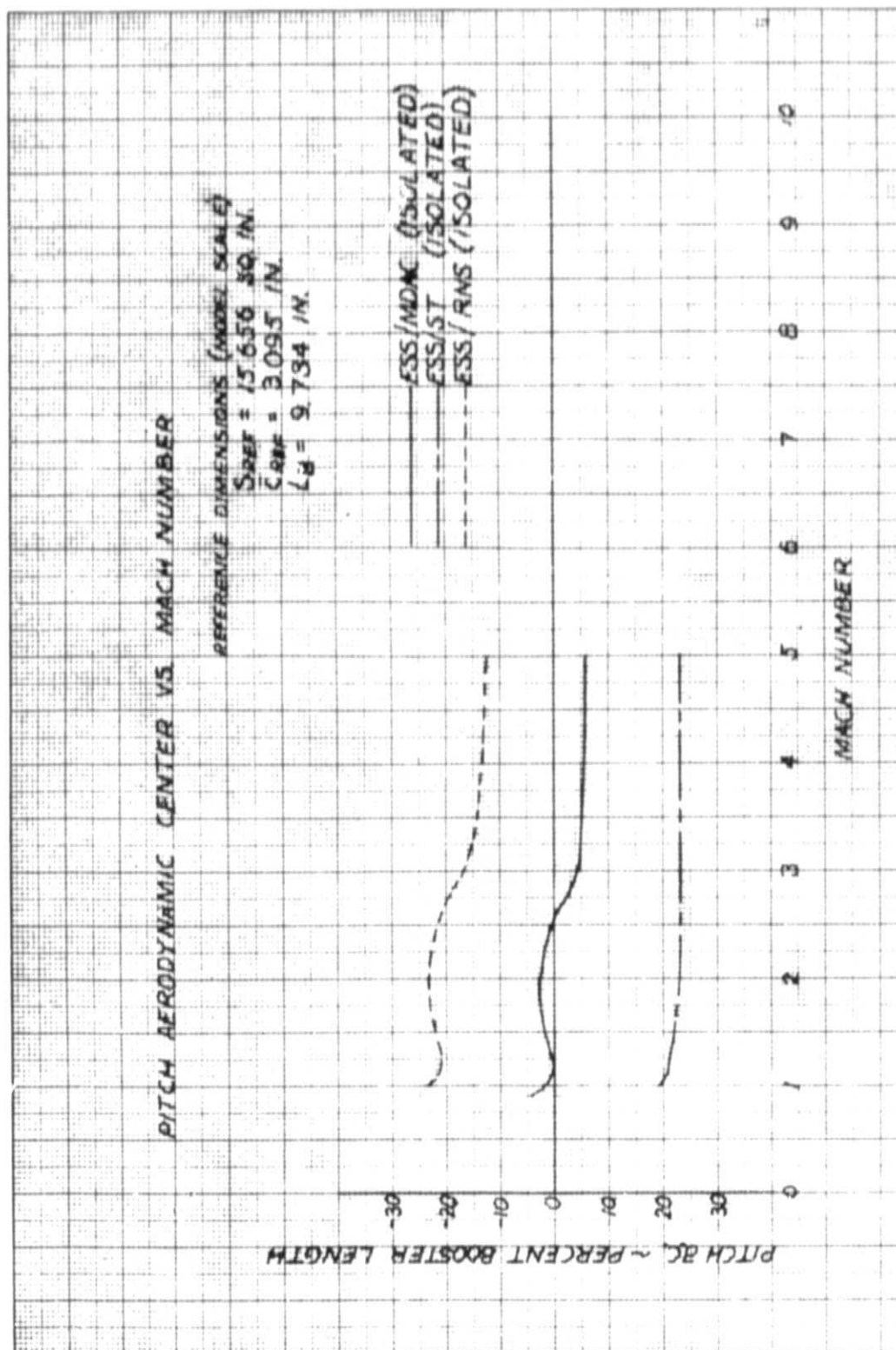


Figure 4-19. Isolated ESS/Payload Stability Characteristics



5.0 CONCLUSIONS

The following conclusions are based on the analysis presented;

1. Static stability can be maintained in pitch for $M \leq 5.0$ with center of gravity locations of 48, 54, and 58 percent of the booster length for the RNS, MDAC and space tug payload configurations, respectively.
2. Static stability in yaw requires a center of gravity location approximately 14 percent of the booster length forward of that required for static pitch stability.
3. Adequate elevon roll control is provided. For example, the ESS/RNS plus booster launch configuration at the flight condition of $M = 1.2$ and $\alpha = -6$ can control roll due to yaw with 0.5 degree differential control deflections per each degree of sideslip angle (roll referenced at the booster centerline).

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